Advanced Exploration Systems (AES) Logistics Reduction and Repurposing Project: Advanced Clothing Ground Study Final Report

Crew and Thermal Systems Division

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Advanced Clothing Ground Study Final Report

Concurrence Sheet

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Change Record

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LIST OF ACRONYMS AND VARIABLES

Acronym	Definition
ACS	Advanced Clothing System
AES	Advanced Exploration Systems
ANOVA	Analysis of Variance
COTS	Commercial Off The Shelf
CP	Cotton and Polyester
CPW	Cotton, Polyester, and Wool
CPWG	Crew Provisioning Working Group
CTB	Cargo Transfer Bag
DSH	Deep Space Habitat
FY	Fiscal Year
HMC	Heat Melt Compactor
IRB	Institutional Review Board
ISS	International Space Station
JSC	Johnson Space Center
L2L	Logistics to Living
LRR	Logistics Reduction and Repurposing
MMSEV	Multi-Mission Space Exploration Vehicle
NASA	National Aeronautics and Space Administration
PMC	Polyester, Modacrylic, and Cocona
SE&I	Systems Engineering and Integration
TIM	Technical Interchange Meeting
TTG	Trash to Gas
US	United States

1.0 EXECUTIVE SUMMARY

All human space missions require significant logistical mass and volume that will become an excessive burden for long duration missions beyond low Earth orbit. The goal of the Advanced Exploration Systems (AES) Logistics Reduction & Repurposing (LRR) project is to bring new ideas and technologies that will enable human presence in farther regions of space. The LRR project has five tasks: 1) Advanced Clothing System (ACS) to reduce clothing mass and volume, 2) Logistics to Living (L2L) to repurpose existing cargo, 3) Heat Melt Compactor (HMC) to reprocess materials in space, 4) Trash to Gas (TTG) to extract useful gases from trash, and 5) Systems Engineering and Integration (SE&I) to integrate these logistical components.

The current International Space Station (ISS) crew wardrobe has already evolved not only to reduce some of the logistical burden but also to address crew preference. The ACS task is to find ways to further reduce this logistical burden while examining human response to different types of clothes. The ACS task has been broken into a series of studies on length of wear of various garments: 1) three small studies conducted through other NASA projects (MMSEV, DSH, HI-SEAS) focusing on length of wear of garments treated with an antimicrobial finish; 2) a ground study, which is the subject of this report, addressing both length of wear and subject perception of various types of garments worn during aerobic exercise; and 3) an ISS study replicating the ground study, and including every day clothing to collect information on perception in reduced gravity in which humans experience physiological changes.

The goal of the ground study is first to measure how long people can wear the same exercise garment, depending on the type of fabric and the presence of antimicrobial treatment, and second to learn why. Human factors considerations included in the study consist of the Institutional Review Board approval, test protocol and participants' training, and a web-based data collection questionnaire. Cardiovascular exercise was chosen as the activity in this experiment for its profuse sweating effect and because it is considered a more severe treatment applied to the clothes than every-day usage. Study garments were exercise T-shirts and shorts purchased from various vendors. Fabric construction, fabric composition, and finishing treatment were defined as the key variables.

The study was divided into three balanced experiments: a cotton-polyester-wool (CPW) T-shirts study with 61 participants, a polyester-modacrylic-polyester/cocona (PMC) T-shirts study with 40 participants, and a shorts study with 70 participants. In the CPW study, the T-shirts were made of 100% cotton, or of 100% polyester or of 100% wool, and categorized into open and tight knit constructions. In the PMC study, the T-shirts were made of 100% polyester, or of 82% modacrylic, or of 95% polyester with 5% cocona fiber, without construction distinction. The shorts were made either of 100% cotton or of 100% polyester, and were knitted or woven. Some garments were treated with Bio-Protect 500 antimicrobial finish according to the experimental design. The data collected from the questionnaire included garment identification, level of exertion, duration of exercise session, number of exercise sessions, an ordinal preference scale for nine sensory elements, and reason for retiring a used garment.

From the analysis of the combined CPW and PMC shirt studies, there are statistically significant differences among the mean lifetimes of various types of shirts. The exercise shirts with the longest mean lifetimes are untreated wool (600 minutes), treated cotton (526 minutes), and untreated modacrylic (515 minutes). From the combined CPW and PMC shirt studies, the most preferred material was untreated open-knit wool, which is one of the two materials that jointly were worn the longest, untreated wool, both open-knit and tight-knit.

For the CP shorts study, there were no statistically significant differences in mean lifetimes of the exercise shorts at the 5% significance level due to the treatment combinations. There was therefore no justification to examine differences among levels of main effects or interactions. The preference for shorts was in this order: untreated woven polyester, untreated knitted polyester, untreated woven cotton, and treated knitted cotton.

The nine preference scales were tabulated to determine the preference responses at the end of those exercise periods which were prior to the period when a garment was retired and a new garment was started. The assumption is that an unfavorable assessment of a garment leads to its retirement. The scent scale response was predominantly unfavorable at the end of the exercise period immediately prior to the exercise period when a new garment was started.

Future work should address the merit of other antimicrobial agents depending on how the types of fabric are combined. Additional work on wool clothing is needed to verify that this material can be part of a crew wardrobe for long duration missions.

2.0 INTRODUCTION

2.1 Background

2.1.1 Logistics Reduction and Repurposing Project

All human space missions, regardless of destination, require significant logistical mass and volume that increase with mission duration. As our exploration missions lengthen in distance and duration, reduction in mass and volume becomes even more important, since all cargo must be loaded on a single launch vehicle. This project targets the best opportunities to demonstrate logistics reduction and repurposing. New technologies and innovative ideas will make future exploration missions much more affordable.

The Advanced Exploration Systems (AES) Logistics Reduction and Repurposing (LRR) project will enable a largely mission-independent cradle-to-grave-to-cradle approach to minimize logistics contributions to total mission architecture mass. Its goals are to:

- Minimize intrinsic logistics mass and improve ground logistics flexibility.
- Allow logistics components to be directly repurposed for on-orbit non-logistics functions (e.g., crew cabin outfitting) – thereby indirectly reducing mass/volume.
- Compact or process logistics that have not been directly repurposed to generate useful on-orbit components and/or compounds (e.g., radiation shielding, propellant, other usable chemical constituents).
- Enable long-term stable storage and disposal of logistics end products that cannot be reused (e.g., compaction for volume reduction, odor control, and maintenance of crew cabin hygienic conditions).
- Allow vehicles in different mission phases to share logistics resources.

The goals of the Logistics project will be accomplished through four hardware tasks plus a strong systems engineering analysis and integration function. The four hardware-oriented tasks are:

- Use of an Advanced Clothing System (ACS) to reduce mass and volume, while meeting materials flammability requirements. For a crew of four on a one year mission, ACS strives to reduce the crew clothing mass and volume by 50%.
- Use of logistics-to-living (L2L) to repurpose launch packaging containers for crew equipment. For a one year mission, it is estimated that over 100 Cargo Transfer Bags (CTBs) would be available for repurposing.
- Recycling of logistical items via heat melt compactor (HMC) processing. For a one year mission, it is estimated that HMC could recover ~10 cubic meters of volume and produce over 800 kg of radiation shielding tiles.
- Conversion of trash to gas (TTG) to make propellant from waste products. For a one year mission, it is estimated that TTG could produce up to 1400 kg of methane from trash.

The Systems Engineering and Integration (SE&I) group will determine which logistics components and quantities should be targeted for particular hardware technologies, e.g. ACS, L2L, HMC, and TTG. Additionally, it will identify how logistical components themselves should be tailored or changed to improve their repurposing.

2.1.2 Advanced Clothing System Task

Advanced lightweight and antimicrobial fabrics that extend the useful life of spaceflight clothing while reducing costs, up-mass, and disposal burden will help enable long-duration missions beyond Low Earth Orbit (LEO). Clothing accounts for a significant portion of the logistical mass launched on current space missions: 451 kg for an International Space Station (ISS) crew of six each year (not counting towels). Since there is currently no laundering capability on the space station, the clothes becomes trash when too dirty to wear.

In this task, the repeated use of lightweight and antimicrobial garments by subjects will be assessed for their effect on comfort, appearance, and odor. The fabrics selected from commercial-off-the-shelf (COTS) sources will also be evaluated for flammability in spacecraft atmospheres at different oxygen levels. In addition, the SE&I task will evaluate candidate fabrics for their potential repurposing in the HMC or TTG systems under LRR.

Figure 1. ACS Shirt in MMSEV Test

In the first fiscal year (FY12), the task consisted of selecting clothing articles and evaluating their performance via flammability tests, functional tests, and during short duration (1-2 week) ground tests with the Multi-Mission Space Exploration Vehicle (MMSEV) and Deep Space Habitat (DSH). Figure 1 shows a MMSEV crew member wearing the ACS supplied shirt during its integrated ground test.

The second year (FY13) of this task was spent in developing and conducting a ground study with approximately 80 participants. This study focused on evaluating various fibers and fabrics, as well as the use of antimicrobial treatment, to determine the average length of time they can be worn. In addition, the ACS team collaborated with the Hawaii Space Exploration Analog and Simulation (HI-SEAS) mission to evaluate exercise shirts and sleep shirts over a 16 week period. The HI-SEAS crew exercised daily wearing the shirts provided by the ACS task (Figure 2).

Figure 2. HI-SEAS Crew in ACS Provided Shirts

The third year (FY14) of the ACS task will culminate in an ISS technology demonstration during Increments 39 through 42 to evaluate selected shirts and shorts for exercise or routine activities. ACS will also work with the ISS Mission Integration and Operations Office to identify collaborative efforts to address lint generation and long wear clothing options for the crew catalog.

2.1.3 ISS Baseline

Crew members inhabit the ISS for 6 months at a time supporting their expedition. These long duration missions necessitate a well thought-out process for crew provisioning. The ISS Crew Provisioning Working Group (CPWG) was established in 1998 to develop the requirements and process for provisioning clothing, hygiene items, crew preference items, office supplies, and food. The CPWG approves the Joint Crew Provisioning Catalog which contains all crew provisioning items (except food) that have been certified for use on ISS.

United States (US) clothing for ISS evolved to include cargo pants and shorts, color options for cotton shirts, new styles for socks, underwear, and exercise clothes. Exercise T-shirts containing X-Static fibers were added to the catalog. Clothing items from the catalog are selected after fit-check events held in Houston and Star City.

The choice of clothes and their usage rates for ISS missions (shown on Table 1) has been made firstly to address a tight schedule among work, exercise, and sleep time, with little allocation for garment care, and secondly to address individual preferences of crew members. Over the years, the crew wardrobe has changed to address new needs such as that of pockets in pants or color options in shirts. Crew debriefs held after each missions are essential to gather the information that leads to these changes. Furthermore, since the human body experiences metabolic and physiological changes in microgravity, it is also crucial to understand how these affect the astronauts' perception of their clothing.

The usage rates and mass of various clothing items defined in the Joint Crew Provisioning Catalog, Revision B, are provided in Table 1.

Table 1. Clothing Usage Rates

Name	**Mass (kg)**	**Usage Rate (No. of days)**	**No. of Items for 1 Year**
Crew Preference Shirt (Long Sleeve)	0.55	15	13
Crew Preference Shirt (Short Sleeve)	0.45	15	13
Cargo Shorts	0.35	30	5
Cargo Pants	0.65	30	7
Trousers	0.6	30	3
X-Static T-Shirt	0.3	14	27
Colored T-Shirt	0.25	7	53
Underwear	0.1	2	183
X-Static Crew Socks	0.08	14	27
Crew Socks, White	0.08	7	53
Athletic Shorts	0.15	7	53
Total Mass (kg) - 1 Crew	75		
Total Mass (kg) - 6 Crew	**451**		

2.1.4 Human Factors

Given the objectives of the Advanced Clothing System (ACS) Exercise Wear Study**,** it is very important to gain the perspective of the human population expected to wear the clothing. While technical properties (e.g., mass, shelf-life, wicking properties of garments) provide valuable information, these need to be complemented with human-in-the-loop studies (i.e., subjects wearing the clothing during exercise) along with the collection of subjects' feedback. How long a person continues to wear the exercise clothing (for multiple sessions) before it is deemed to be non-wearable and the reasons leading to the discontinued use (e.g., odor or discomfort) are of interest. It is the subject's decision to continue to wear exercise shirts and shorts, as it would be in normal life situations.

Because the nature of clothing wear involves a subjective component, it was important to design the ground study's data collection questionnaire in an unbiased fashion in order to evaluate each shirt and shorts tested. The human factors elements involved usability and human performance expertise to contribute to the design of test protocols, training, web-based data collection questionnaire, and development and submission of the study protocol to the NASA Institutional Review Board (IRB) for study approval.

2.2 Overview

The goal of the ground-based clothing experiments is to evaluate clothing for extended wear in terms both of effectiveness and of subjects' perception and acceptance of long term wear.

This ground-based experiment was designed to study the effectiveness of garments made with various fabrics for extended wear. It was hypothesized that wear can be extended by preventing or reducing microbial growth which causes objectionable odors and other effects in fabrics. Garments made from two natural fibers, cotton and wool, and from two synthetic fibers, polyester and modacrylic, were selected for this study. Cotton represented the baseline, as it is the main fiber component of the current crew wardrobe, while polyester and wool, also present in the wardrobe, are only used in sleepwear and socks. On the other hand, modacrylic is new to space applications.

Cardiovascular exercise was chosen as the activity in this experiment for its profuse sweating effect and because it was considered a more severe treatment applied to the clothes than every day usage. Some garments were treated with an antimicrobial agent, and some garments were untreated. Fabric construction, fabric composition, and finishing treatment were defined as the other main variables in this study.

3.0 PROCESS

3.1 Objectives

The primary objective of the study is to estimate the length of time that exercise clothing can be used before it is found to be objectionable to the wearer depending on the type of fabric and the type of antimicrobial treatment.

An additional objective is to correlate nine sensory perception responses to the garments with the type of fabric and the type of antimicrobial treatment.

Differences in length of wear of shirts or shorts were estimated as a function of fabric type and antimicrobial treatment. No hypotheses are known or proposed concerning the size of such differences. The detection of any statistically significant and materially significant differences may provide guidance not only for future research but also for the composition of the crew provisioning catalog.

No hypotheses are known or proposed concerning any associations between sensory perception responses to the exercise garments and the type of fabric and the type of antimicrobial treatment. The detection of any statistically significant associations may provide guidance not only for future research but also for the composition of the crew provisioning catalog.

The primary outcomes for length of usage were calculated from daily questionnaire data. These outcomes are cumulative number of exercise sessions and cumulative exercise time before a garment is retired from use.

The secondary outcomes for sensory perception are the responses on an ordinal preference scale to each of nine sensory assessments.

3.2 Clothing Selection

The choice of fabric composition in terms of fiber type and percent content was driven by functionality and appearance. Today's athletic clothing is mostly made of polyester for various reasons: polyester is hydrophobic enough to wick moisture and not absorb water like cotton, which results in quicker drying time. This alone affects comfort and microbial growth, and consequently odor. In addition, since polyester dominates the man-made fiber world (over 94.7 billion pounds/year produced in the last three years[1]) and is available in a wide range of linear densities, athletic apparel designers have been able to engineer garments with a marketable balance of functionality and comfort. Hence, polyester garments are the first one selected in this experiment. The choice of the other two types of fibers for this study was also based on factors that affect length of wear such as odor, comfort, and appearance. Merino wool base layers were chosen because some of the inherent characteristics of the fiber are desirable for use in space apparel and because of the technical progress made by the wool industry to make wool more attractive to consumers. Modacrylic was chosen because it has the same physical properties that make wool a candidate fiber for this study.

Initially, it was intended to include shirts made with polyester yarn containing an antimicrobial copper oxide. The vendor of these shirts intended to put them on the market soon, and the ACS task attempted to obtain a sufficient number of pre-market shirts. However, these shirts containing copper oxide were not available in time for this study. Polyester shirts containing cocona fibers were used in place of the shirts containing copper oxide. The cocona fibers were reputed to have antimicrobial properties.

Due to the limited availability of certain types of fabrics and knits, the study was divided into three experimental designs, two designs for exercise shirts and one design for exercise shorts.

3.3 Experimental Design

It is hypothesized that the duration of garment wear can be extended by preventing or reducing microbial growth which causes objectionable odors and other objectionable effects in fabrics. Garments made from two natural fibers, cotton and wool, and from two synthetic fibers, polyester and modacrylic, were used in exercise clothing consisting of T-shirts and shorts. Some garments were treated with an antimicrobial treatment (Bio-Protect 500 from PureShield, Inc.), and some garments were untreated.

Due to the limited commercial availability of certain types of fabrics and knits, the study was divided into three experimental designs, two designs for exercise T-shirts and one design for exercise shorts.

Balanced experimental layouts were used in each experimental design with equal numbers of treated and untreated garments in order to assess the effectiveness of natural and treated fibers on the aerobic exercise time required for a garment to become objectionable for wear by the study participants.

The first experimental design is for exercise T-shirts available in both open knit and tight knit fabrics and is for the Cotton, Polyester, and Wool (CPW) shirt study. The CPW experiment was run concurrently with the second experiment described below for exercise shorts. A single replicate is displayed below. It is a full factorial design with three factors (Fiber, Knit, and Antimicrobial) in three, two, and two levels, respectively.

[1] http://www.textileworld.com/Articles/2013/October/The_Rupp_Report_The_Shift_In_Global_Man-made_Fibers_Production.html

Table 2. Open/Tight Knit T-Shirts Single Replicate

	Fiber	Knit	Antimicrobial
1	cotton	open knit	Bio-Protect 500
2	cotton	open knit	untreated
3	cotton	tight knit	Bio-Protect 500
4	cotton	tight knit	untreated
5	polyester	open knit	Bio-Protect 500
6	polyester	open knit	untreated
7	polyester	tight knit	Bio-Protect 500
8	polyester	tight knit	untreated
9	wool	open knit	Bio-Protect 500
10	wool	open knit	untreated
11	wool	tight knit	Bio-Protect 500
12	wool	tight knit	untreated

The T-shirts were worn by participants until deemed by the wearer as no longer acceptable to wear. The requested minimum number of daily exercise sessions is 15. Participants can stop at any time but were strongly requested not to exceed 30 daily exercise sessions. Exercise days did not need to be consecutive, but an excessively long interruption of, say, one or two weeks might have been considered equivalent to withdrawing from the study.

An analysis of variance (ANOVA) table for 48 exercise T-shirts (four replicates) is given below for the extreme case in which the T-shirt is not withdrawn from use during any participant's time in the study. If some T-shirts are withdrawn from use and replaced during the time in the study, then the number of useful observations will be larger. In the ANOVA table, the first column gives a factor or a combination of factors (called an interaction), and the second column give the ANOVA degrees of freedom (df).

The analysis of variance concept is useful in assessing the adequacy of both the experimental design and the sample size, since it is reasonable to expect that a simple nonlinear function of the length of wear will be normally distributed. This function may be the logarithm or a power of the wear time. In statistics, such a function is often called a Box-Cox transformation.

Table 3. ANOVA for 48 T-Shirts

Factor or Interaction	df
Mean	1
Fiber	2
Knit	1
Antimicrobial	1
Fiber*Knit	2
Fiber*Antimicrobial	2
Knit*Antimicrobial	1
Fiber*Knit*Antimicrobial	2
Error for n = 48	36
Total	**48**

The degrees of freedom for error are the sample size minus the sum of degrees of freedom for factors and interactions. If no participant changes a shirt, then four replicates require 48 participants and result in 36 degrees of freedom for error. If shirts are changed, then the sample size and the degrees of freedom for error increase accordingly.

The second experimental design is for exercise shorts, which are available in cotton and polyester, in both knitted and woven fabric, and is abbreviated as the CP shorts study. A single replicate is displayed below. It is a full factorial design with three factors (Fiber, Construction, and Antimicrobial), each factor in two levels.

Table 4. Shorts Single Replicate

	Fiber	**Construction**	**Antimicrobial**
1	cotton	knitted	Bio-Protect 500
2	cotton	knitted	untreated
3	cotton	woven	Bio-Protect 500
4	cotton	woven	untreated
5	polyester	knitted	Bio-Protect 500
6	polyester	knitted	untreated
7	polyester	woven	Bio-Protect 500
8	polyester	woven	untreated

The rules for wearing shorts are the same as those above for wearing T-shirts. As will be seen from the analysis of variance table below, not as many shorts are needed in the study as T-shirts. Study exercise shorts and T-shirts were worn at the same time until such time as the study had accrued the requisite number of shorts-wearing participants. This meant that some participants supplied their own exercise shorts while wearing study T-shirts.

An analysis of variance table for 40 exercise shorts (five replicates) is given below for the extreme case in which the shorts are not withdrawn from use during any participant's time in the study. If some shorts are withdrawn from use and replaced during the time in the study, then the number of useful observations will be larger.

Table 5. ANOVA for 40 Shorts

Factor	**df**
Mean	1
Fiber	1
Construction	1
Antimicrobial	1
Fiber* Construction	1
Fiber*Antimicrobial	1
Construction *Antimicrobial	1
Fiber* Construction *Antimicrobial	1
Error for n = 40	32
Total	**40**

If no participant changes shorts, then five replicates will require 40 participants and will result in 32 degrees of freedom for error. If shorts are changed, then the sample size and the degrees of freedom for error increase accordingly.

The third experimental design is for exercise T-shirts available only in tight knit fabrics and is for the Polyester, Modacrylic, and Cocona (PMC) shirt study. This experiment will look at the length of wear for modacrylic T-shirts and polyester/cocona blend T-shirts. The single replicate displayed below shows how these T-shirts, both treated and untreated, will be compared with each other and with polyester T-shirts that are not polyester/cocona blend T-shirts.

Table 6. Special Fiber Shirts Single Replicate

	Fiber - tight knit	**Antimicrobial**
1	non-polyester/cocona blend polyester	untreated
2	non-polyester/cocona blend polyester	Bio-Protect 500
3	modacrylic	untreated
4	modacrylic	Bio-Protect 500
5	polyester/cocona blend	untreated
6	polyester/cocona blend	Bio-Protect 500

The rules for wearing T-shirts in this experiment are the same as those above in the first experiment. An analysis of variance table for 36 exercise T-shirts (six replicates) is given below for the extreme case in which the T-shirt is not withdrawn from use during any participant's time in the study. If some T-shirts are withdrawn from use and replaced during the time in the study, then the number of useful observations will be larger.

Table 7. ANOVA for 36 T-Shirts

Factor	**df**
Mean	1
Fiber	2
Antimicrobial	1
Fiber*Antimicrobial	2
Error for n = 36	30
Total	**36**

Data from the tight knit polyester T-shirts from the CPW shirt study were pooled with this experiment's data. In this way, fewer non-polyester/cocona blend polyester T-shirts were needed to complete the six replicates. This experiment will require 28 subjects, since data from eight subjects in the first experiment will be used in the analysis of this experiment. If no participant changes a shirt, then six replicates require 36 participants and result in 30 degrees of freedom for error. If shirts are changed, then the sample size and the degrees of freedom for error increase accordingly.

Randomization of treatment combinations was performed separately for each replicate of each experimental design. A treatment combination is the same as a row in the replicates displayed in Table 2, Table 4, and Table 6. Randomization of the treatment combinations means ordering the rows randomly. Study participants were assigned as they were accrued to treatment combinations according to the sequential order of the rows in the randomized replicates. When feasible, due to the availability of garments in specific sizes and due to the sensitivity of some participants to certain materials, notably to wool, replicates were, for the most part, completely assigned before using the next replicate.

Due to the nature of this study, it was not possible in all cases to conceal from participants the type of fiber in the exercise clothing. However, participants were not told if the garments are treated or untreated. Experience with the Bio-Protect 500 treatment indicates that only a trained observer is likely to detect the presence of this treatment. Therefore, with respect to responses on the perception scales, no bias from participants is expected due to the presence of antimicrobial treatment.

Almost no data were available for the usual sample size calculations. The sample sizes for the experimental designs were determined by the number of replicates needed to have at least 30 degrees of freedom for error in a full analysis of variance with main effects and all interactions. The sample sizes are the numbers of shirts and shorts needed, not the number of subjects. The number of subjects needed is a consequence of the numbers of shirts and shorts needed.

The number of replicates is determined by the primary objective of length of wear under the extreme case that no subject ever retires his garment from use. If garments are retired and replaced during the period of exercise participation, then the garment sample size will be larger.

Limited preliminary data was available for the length of wear of polyester exercise T-shirts treated with Bio-Protect 500. In the Deep Space Habitat (DSH) study, four crew members lived in the vehicle for two consecutive weekday periods of five days Monday through Friday. Each crew member was supposed to perform two periods of exercise each day, although some crew members missed one or more exercise periods. Two T-shirts were retired from use and replaced with fresh T-shirts, one shirt after 5 days and the other after 6 days.

Under the assumption that each DSH exercise session was nominally one hour, the following table gives the T-shirt wear experience. Hours of wear marked with an asterisk are right-censored, that is, the shirt was still being worn when the study ended, so that the actual lifetime of the shirt lay sometime in the future. However, censoring is not considered in the analysis of these data due to the very small sample size and to the preliminary nature of the data.

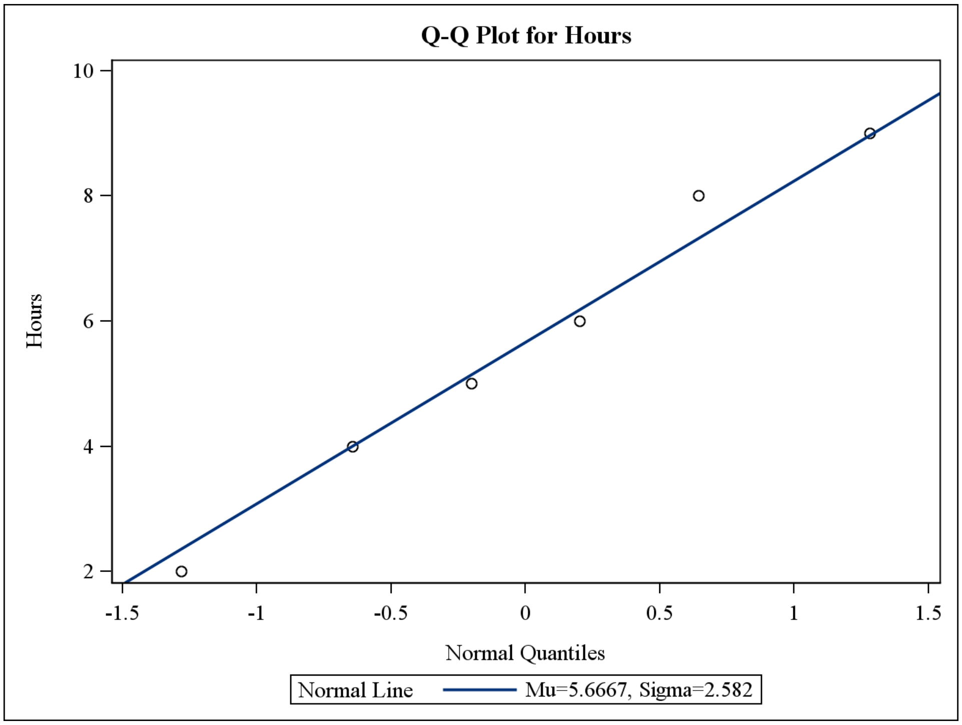
Table 8. DSH T-Shirt Wear

Subject Nr	Shirt Nr	Hours
1	1	5
1	2	4*
2	3	9
3	4	6
3	5	2*
4	6	8

A normal quantile plot of the DSH data shows that hours of wear are normally distributed with a mean of 5.7 and a standard deviation of 2.6. The Kolmogorov-Smirnov test against the null hypothesis that the data are normally distributed has a p-value greater than 15%, and thus the null hypothesis of normality is not rejected.

Table 9. Probability Plot of DSH T-Shirt Wear Hours				
Tests for Normality				
Test	**Statistic**		**p Value**	
Kolmogorov-Smirnov	**D**	0.150255	**Pr > D**	>0.1500

Figure 3. Normal Quantile Plot of DSH T-Shirt Wear Hours



A normal power analysis with a statistical size of 5% based on the DSH T-shirt data shows that there is a statistical power of at least 80% of detecting a difference of 2.55 hours of wear from the mean of 5.66 hours with a sample of 8 T-shirts. Eight T-shirts is the minimum number of Bio-Protect 500 treated polyester T-shirts expected from the first and third experiments, including polyester/cocona blend T-shirts, given that some T-shirts are expected to be retired. For the CPW T-shirt study, there are at least 4 replicates with at least 2 Bio-Protect 500 treated polyester T-shirts in each replicate. This gives at least 8 treated polyester T-shirts. In the PMC T-shirt study, there are at least 6 replicates with at least 2 Bio-Protect 500 treated polyester T-shirts in each replicate. This gives at least 12 treated polyester T-shirts. While this difference in length of wear for DSH T-shirts is interesting by itself and adequate for showing improved performance, very little importance should be ascribed to this finding due to its scope being limited to Bio-Protect 500 treated T-shirts. The DSH study provided the only data on length of wear for Bio-Protect 500 treated polyester T-shirts prior to the ACS Ground Study. Nevertheless, this finding for DSH T-shirts is consistent with the choice of sample size for the ACS ground study. A statistical power analysis such as this, usually based on prior limited data, is customary for the estimation of required sample size for a larger formally designed study such as the present ACS ground study.

Table 10. Power vs Hours and Shirts		
Computed Nr of Shirts		
Hours	**Power**	**Shirts**
8.01	0.801	9
8.06	0.815	9
8.11	0.829	9
8.16	0.842	9
8.21	0.807	8
8.26	0.820	8
8.31	0.832	8
8.36	0.844	8
8.41	0.855	8
8.46	0.811	7
8.51	0.823	7
8.56	0.834	7
8.61	0.845	7
8.66	0.855	7

3.4 Institutional Review Board

In order to perform the ground study, the NASA IRB regulatory process was required. The NASA IRB committee monitors the flow of information and the associated activities and tasks for all participants. The ACS task's approval for the ground study protocol was received on 1/18/13. The protocol and human subjects' consent form contained important information related to participation in a research study including the purpose, planned procedures, potential risks and data privacy. This ground study was categorized as "reasonable risk." This is defined by NASA IRB as "the probability and magnitude of harm or discomfort anticipated in the research are greater in and of themselves than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests, but that the risks of harm or discomfort are considered to be acceptable when weighed against the anticipated benefits and the importance of the knowledge to be gained from the research." The risks all related to the exercise task component and included: fatigue, cardiac rhythm problem or remote risk of heart attack, skin discomfort/minor irritation, muscular soreness, and exercise equipment hazards. Risk mitigations were put in place and presented clearly in the informed consent forms that the participants received and signed.

3.5 Recruitment

Subjects were recruited through JSC Today email announcements and flyers posted around the JSC buildings and cafeterias. Due to the exercise requirement, the recruitment of subjects for this study involved the JSC Test Subject Facility (TSF). The TSF performed the screening and eligibility. In order to participate, all subjects were required to pass a Class III Test Subject Physical based on the Modified Air Force Class III Medical Standard. These physicals were set up and provided by the TSF. Once it was determined that a subject passed the physical, the TSF personnel provided his/her name and contact information to the ACS ground study coordinator. The coordination with the TSF was one part of the risk mitigation plan for the health risks associated with exercise.

Informed consent and training sessions were held with groups of interested participants prior to the start of the study. The meetings presented interested participants with an overview of the study, instructions on how to complete the web questionnaire, safety video about exercising at the Gilruth Center, and collection of informed consent forms. Once the informed consent forms were signed by the participants, they received their study assignments and the study team received their sizing information.

3.6 Logistics

Since the study addressed both effectiveness of the garment in terms of length of wear and acceptance, the study team developed the following experimental framework.

3.6.1 Duration

This study asked participants to complete 15 exercise sessions; each session consisting of 45 -60 minutes of cardiovascular exercise.

3.6.2 Location

A common indoor location was imposed on all participants in order to have controlled ambient conditions throughout the experiment. Since the participants were NASA employees and contractors, the experiment was conducted in the NASA Gilruth Center Fitness Room and Spinning Studio.

3.6.3 Participants

In the effort to recruit participants who were able to perform the experiment in the designated location, two inclusion criteria were imposed on the candidates. First, only NASA employees and their contractors were eligible, and second, all candidates were required to pass a medical evaluation to be accepted as subjects in this exercise clothing study. Hence, the study group was composed of individuals with common fitness levels, as well as shared local norms, conditions, and corporate culture. As of the 9/19/2013 data cut-off date, the total number of participants recruited in this study was 94, and 76 participants completed the study.

3.6.4 Exercise Session Instructions

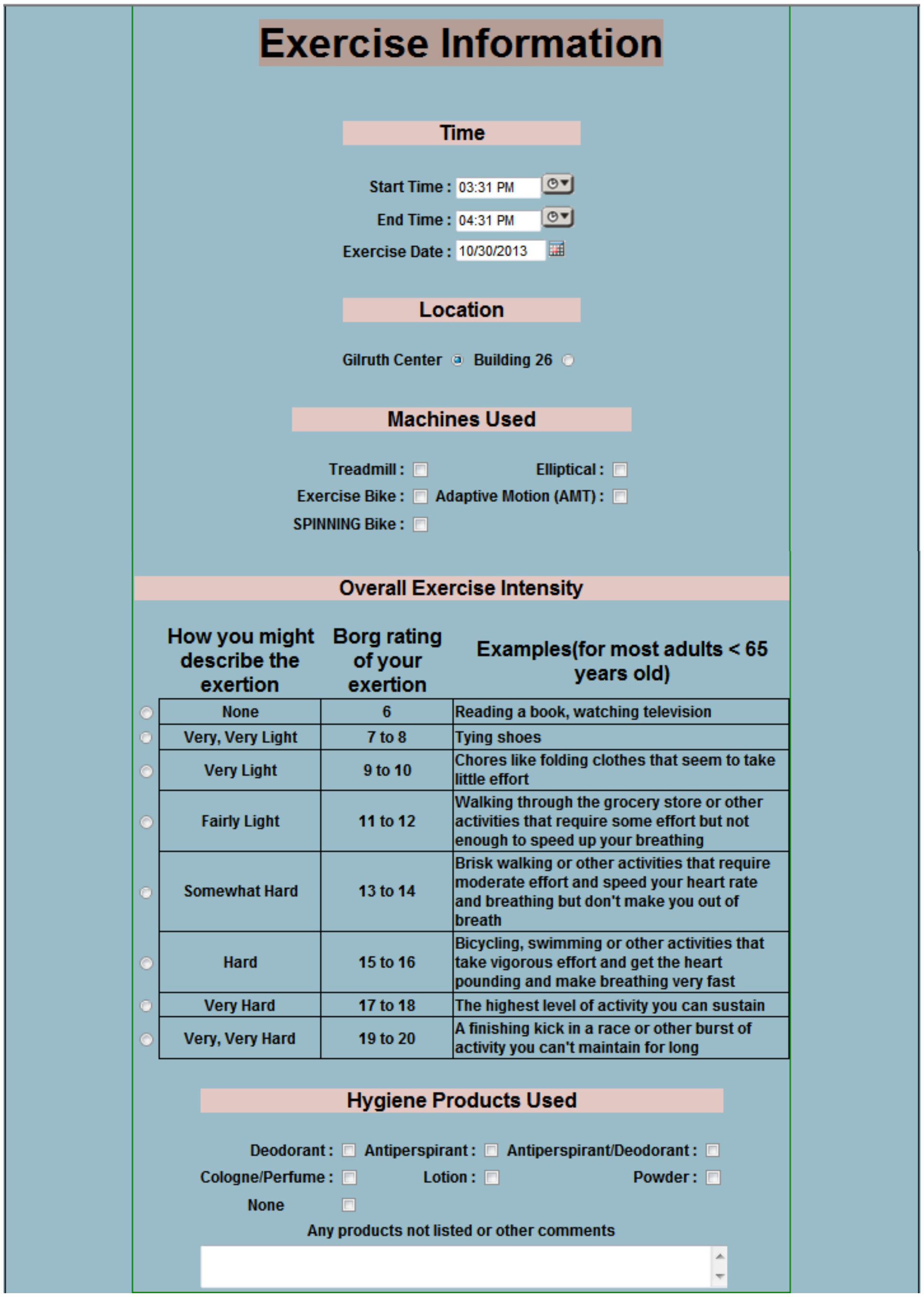
The training session each participant attended included these instructions.

- To perform cardiovascular exercise between 45 and 60 minutes on any single or combination of the machines approved for the study (treadmills, ellipticals or stationary bikes and spinning bikes).
- To exercise at a level of 13 or greater as described below on the Borg scale of perceived exertion.
- To hang the clothes in a ventilated area on provided hangers after each exercise session to let them dry completely.
- To fill out the online ACS Exercise Clothing Study Questionnaire.
- Not to wear perfume or cologne on the days of participation in the study.
- Not to leave clothes in gym bags or lockers.
- Not to launder or clean clothes or spray with water or any chemical.

3.6.5 Web Questionnaire

Each participant was requested to complete a questionnaire after each exercise session. The questionnaire consisted of an exercise information section (Figure 4), shirt information section (Figure 5), and if assigned, shorts information section (Figure 6).

Figure 4. Exercise Information Section of Questionnaire



Exercise Information

Time

Start Time : 03:31 PM
End Time : 04:31 PM
Exercise Date : 10/30/2013

Location

Gilruth Center Building 26

Machines Used

Treadmill : Elliptical :
Exercise Bike : Adaptive Motion (AMT) :
SPINNING Bike :

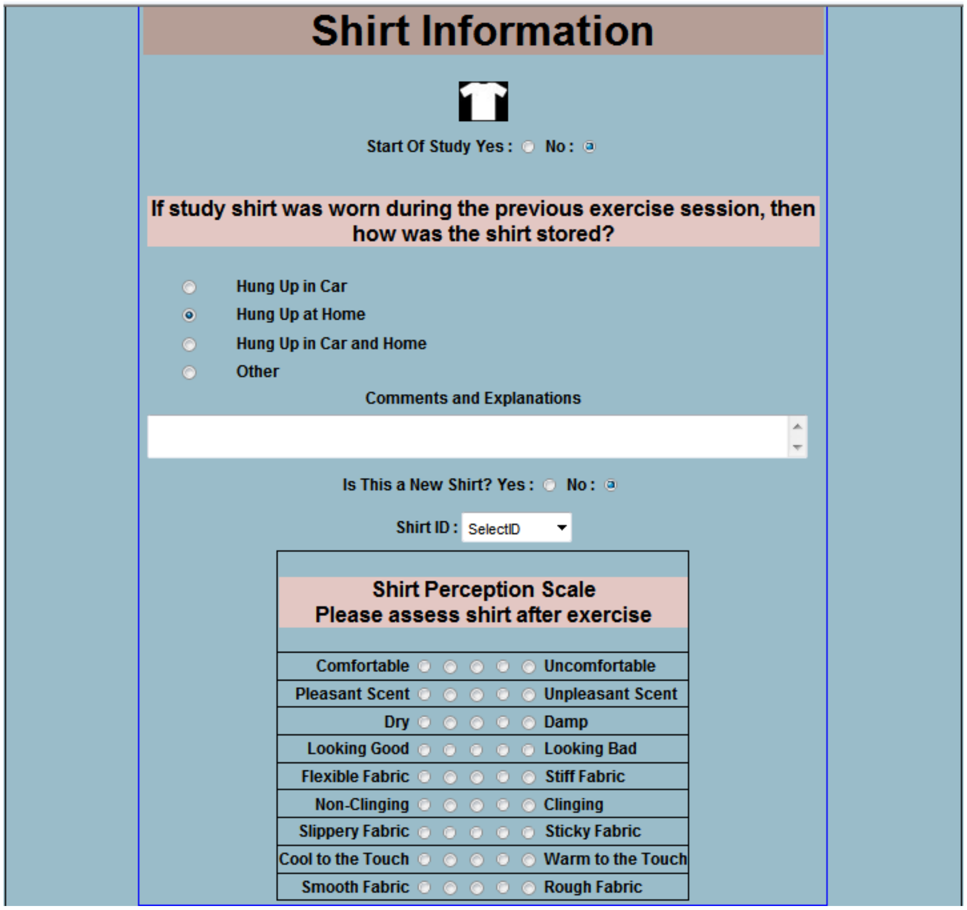
Overall Exercise Intensity

How you might describe the exertion	Borg rating of your exertion	Examples(for most adults < 65 years old)
None	6	Reading a book, watching television
Very, Very Light	7 to 8	Tying shoes
Very Light	9 to 10	Chores like folding clothes that seem to take little effort
Fairly Light	11 to 12	Walking through the grocery store or other activities that require some effort but not enough to speed up your breathing
Somewhat Hard	13 to 14	Brisk walking or other activities that require moderate effort and speed your heart rate and breathing but don't make you out of breath
Hard	15 to 16	Bicycling, swimming or other activities that take vigorous effort and get the heart pounding and make breathing very fast
Very Hard	17 to 18	The highest level of activity you can sustain
Very, Very Hard	19 to 20	A finishing kick in a race or other burst of activity you can't maintain for long

Hygiene Products Used

Deodorant : Antiperspirant : Antiperspirant/Deodorant :
Cologne/Perfume : Lotion : Powder :
None
Any products not listed or other comments

Figure 5. Shirt Information Section of Questionnaire



Shirt Information

Start Of Study Yes : No :

If study shirt was worn during the previous exercise session, then how was the shirt stored?

Hung Up in Car
Hung Up at Home
Hung Up in Car and Home
Other

Comments and Explanations

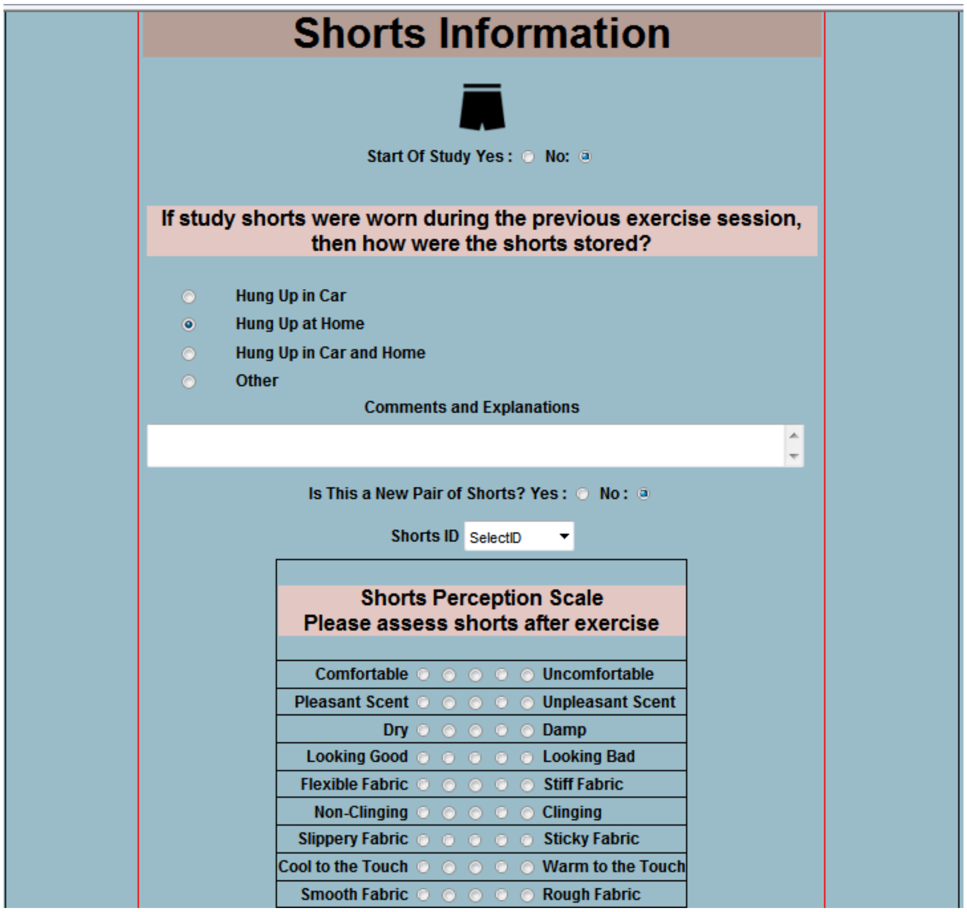
Is This a New Shirt? Yes : No :

Shirt ID : SelectID

Shirt Perception Scale
Please assess shirt after exercise

Comfortable	Uncomfortable
Pleasant Scent	Unpleasant Scent
Dry	Damp
Looking Good	Looking Bad
Flexible Fabric	Stiff Fabric
Non-Clinging	Clinging
Slippery Fabric	Sticky Fabric
Cool to the Touch	Warm to the Touch
Smooth Fabric	Rough Fabric

Figure 6. Shorts Information Section of Questionnaire


Shorts Information

Start Of Study Yes : No:

If study shorts were worn during the previous exercise session, then how were the shorts stored?

- Hung Up in Car
- Hung Up at Home
- Hung Up in Car and Home
- Other

Comments and Explanations

Is This a New Pair of Shorts? Yes : No :

Shorts ID SelectID

Shorts Perception Scale
Please assess shorts after exercise

Comfortable	Uncomfortable
Pleasant Scent	Unpleasant Scent
Dry	Damp
Looking Good	Looking Bad
Flexible Fabric	Stiff Fabric
Non-Clinging	Clinging
Slippery Fabric	Sticky Fabric
Cool to the Touch	Warm to the Touch
Smooth Fabric	Rough Fabric

3.6.5.1 Borg Scale of Perceived Exertion

One way to gauge how hard someone exercises is to use the Borg Scale of Perceived Exertion (Table 11). The Borg Scale takes into account an individual’s fitness level: It matches how hard someone *feels* he is working with numbers from 6 to 20. Thus, it is a "relative" scale.

The scale starts with "no feeling of exertion," which rates a 6, and ends with "very, very hard," which rates a 20. Moderate activities register 11 to 14 on the Borg scale ("fairly light" to "somewhat hard"), while vigorous activities usually rate a 15 or higher ("hard" to "very, very hard").

Dr. Gunnar Borg, who created the scale, set it to run from 6 to 20 as a simple way to estimate heart rate. Multiplying the Borg score by 10 gives an approximate heart rate for a particular level of activity.

Table 11. Borg Scale of Perceived Exertion[2]

How you might describe your exertion	Borg rating of your exertion	Examples (for most adults <65 years old)
None	6	Reading a book, watching television
Very, very light	7 to 8	Tying shoes
Very light	9 to 10	Chores like folding clothes that seem to take little effort
Fairly light	11 to 12	Walking through the grocery store or other activities that require some effort but not enough to speed up your breathing
Somewhat hard	13 to 14	Brisk walking or other activities that require moderate effort and speed your heart rate and breathing but don't make you out of breath
Hard	15 to 16	Bicycling, swimming, or other activities that take vigorous effort and get the heart pounding and make breathing very fast
Very hard	17 to 18	The highest level of activity you can sustain
Very, very hard	19 to 20	A finishing kick in a race or other burst of activity that you can't maintain for long

3.6.5.2 Preference Scale

The sensory perception items are displayed in Table 12 below along with the five-point ordinal response scale. Subjects were left to interpret the sensory items as they saw fit.

Table 12. Preference Scales

Favorable Side	Definitely Favorable	Moderately Favorable	Neutral	Moderately Unfavorable	Definitely Unfavorable	Unfavorable Side
Comfortable	1	2	3	4	5	Uncomfortable
Pleasant Scent	1	2	3	4	5	Unpleasant Scent
Dry	1	2	3	4	5	Damp
Looking Good	1	2	3	4	5	Looking Bad
Flexible Fabric	1	2	3	4	5	Stiff Fabric
Non-Clinging	1	2	3	4	5	Clinging
Slippery Fabric	1	2	3	4	5	Sticky Fabric
Cool Touch	1	2	3	4	5	Warm Touch
Smooth	1	2	3	4	5	Rough

[2] Borg G.A. Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*. 1982; 14:377-381.

4.0 ANALYSIS

4.1 Summary of Participant Population

The results presented in this report are based on data collected by means of the study web site until September 19, 2013 at 2:58 pm, Central Daylight Time. While a small amount of data will be accrued after this date, the incorporation of these additional data will need to be handled in a possible future supplement to this report.

The summary of study participation by gender is displayed in Table 13. Some individuals participated twice, wearing different garment types. They were given new participant identification numbers for their second participation and are counted twice in the summaries below. Participants labeled Yes or No had clothing assigned to them. However, those labeled No or Void never did any exercise.

Table 13. Participation by Gender

Participated	Gender		
Frequency Percent Row Percent Col Percent	Female	Male	Total
Yes	37 35.24 40.66 84.09	54 51.43 59.34 88.52	91 86.67
No	1 0.95 50.00 2.27	1 0.95 50.00 1.64	2 1.90
Void	6 5.71 50.00 13.64	6 5.71 50.00 9.84	12 11.43
Total	44 41.90	61 58.10	105 100.00

For the participants who exercised (the Yes row in Table 13), Table 14 displays the total number of exercise periods by gender, and Table 15 displays total and average exercise hours by gender.

Table 14. Exercise Periods by Gender

Sex	Periods	Percent
Female	502	36.17
Male	886	63.83

Table 15. Exercise Hours by Gender					
Sex	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**
Female	423.85	3.80	11.46	502	0.84
Male	754.62	5.58	13.97	886	0.85

4.2 Summary of Shirt Usage

For the CPW shirt study, the summary of study participation by gender, shirt fabric, shirt knit, and shirt treatment is displayed in Table 16, Table 17, Table 18, and Table 19. The numbers of exercise periods and the numbers of shirts worn by gender, shirt fabric, shirt knit, and shirt treatment are displayed in Table 20, Table 21, Table 22, Table 23, Table 24, Table 25, Table 26, and Table 27. Total exercise hours, standard deviation of total exercise hours, and average exercise hours by participant, by period, and by number of shirts worn for gender, shirt fabric, shirt knit, and shirt treatment are displayed in Table 28, Table 29, Table 30, and Table 31.

For the PMC shirt study, the summary of study participation by gender, shirt fabric, and shirt treatment is displayed in Table 32, Table 33, and Table 34. In the PMC shirt study, there were only tight-knit shirts. The numbers of exercise periods and the numbers of shirts worn by gender, shirt fabric, and shirt treatment are displayed in Table 35, Table 36, Table 37, Table 38, Table 39, and Table 40. Total exercise hours, standard deviation of total exercise hours, and average exercise hours by participant, by period, and by number of shirts worn for gender, shirt fabric, and shirt treatment are displayed in Table 41, Table 42, and Table 43.

Some individuals may have participated twice. They were given new participant identification numbers for their second participation and are counted twice in the summaries below.

Table 16. CPW Shirt Study Participation by Gender		
Sex	**Frequency**	**Percent**
Female	27	44.26
Male	34	55.74

Table 17. CPW Shirt Study Participation by Shirt Fabric		
Shirt Fabric	**Frequency**	**Percent**
Cotton	22	36.07
Polyester	19	31.15
Wool	20	32.79

Table 18. CPW Shirt Study Participation by Shirt Knit		
Shirt Knit	**Frequency**	**Percent**
Open	29	47.54
Tight	32	52.46

Table 19. CPW Shirt Study Participation by Shirt Treatment		
Shirt Treatment	**Frequency**	**Percent**
Bio-Protect 500	30	49.18
Untreated	31	50.82

Table 20. CPW Shirt Study Exercise Periods by Gender		
Sex	**Frequency**	**Percent**
Female	382	40.72
Male	556	59.28

Table 21. CPW Shirt Study Exercise Periods by Shirt Fabric		
Shirt Fabric	**Frequency**	**Percent**
Cotton	311	33.16
Polyester	303	32.30
Wool	324	34.54

Table 22. CPW Shirt Study Exercise Periods by Shirt Knit		
Shirt Knit	**Frequency**	**Percent**
Open	482	51.39
Tight	456	48.61

Table 23. CPW Shirt Study Exercise Periods by Shirt Treatment		
Shirt Treatment	**Frequency**	**Percent**
Bio-Protect 500	471	50.21
Untreated	467	49.79

Table 24. CPW Shirt Study Shirts Worn by Gender		
Sex	**Frequency**	**Percent**
Female	53	51.46
Male	50	48.54

Table 25. CPW Shirt Study Shirts Worn by Shirt Fabric		
Shirt Fabric	**Frequency**	**Percent**
Cotton	42	40.78
Polyester	36	34.95
Wool	25	24.27

Table 26. CPW Shirt Study Shirts Worn by Shirt Knit		
Shirt Knit	**Frequency**	**Percent**
Open	48	46.60
Tight	55	53.40

Table 27. CPW Shirt Study Shirts Worn by Shirt Treatment		
Shirt Treatment	**Frequency**	**Percent**
Bio-Protect 500	48	46.60
Untreated	55	53.40

Table 28. CPW Shirt Study Exercise Hours by Gender							
Sex	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**	**Total Shirts**	**Average Hours per Shirt**
Female	319.03	3.55	11.82	382	0.84	53	6.02
Male	468.48	5.85	13.78	556	0.84	50	9.37

Table 29. CPW Shirt Study Exercise Hours by Shirt Fabric							
Shirt Fabric	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**	**Total Shirts**	**Average Hours per Shirt**
Cotton	269.33	5.11	12.24	311	0.87	42	6.41
Polyester	249.40	2.27	13.13	303	0.82	36	6.93
Wool	268.78	6.72	13.44	324	0.83	25	10.75

Table 30. CPW Shirt Study Exercise Hours by Shirt Knit							
Shirt Knit	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**	**Total Shirts**	**Average Hours per Shirt**
Open	410.48	5.46	14.15	482	0.85	48	8.55
Tight	377.03	4.38	11.78	456	0.83	55	6.86

Table 31. CPW Shirt Study Exercise Hours by Shirt Treatment							
Shirt Treatment	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**	**Total Shirts**	**Average Hours per Shirt**
Bio-Protect 500	395.27	3.31	13.18	471	0.84	48	8.23
Untreated	392.25	6.30	12.65	467	0.84	55	7.13

Table 32. PMC Shirt Study Participation by Gender		
Sex	**Frequency**	**Percent**
Female	15	37.50
Male	25	62.50

Table 33. PMC Shirt Study Participation by Shirt Fabric		
Shirt Fabric	**Frequency**	**Percent**
Modacrylic	12	30.00
Polyester	15	37.50
Polyester/Cocona	13	32.50

Table 34. PMC Shirt Study Participation by Shirt Treatment		
Shirt Treatment	**Frequency**	**Percent**
Bio-Protect 500	20	50.00
Untreated	20	50.00

Table 35. PMC Shirt Study Exercise Periods by Gender		
Sex	**Frequency**	**Percent**
Female	205	33.23
Male	412	66.77

Table 36. PMC Shirt Study Exercise Periods by Shirt Fabric		
Shirt Fabric	**Frequency**	**Percent**
Modacrylic	190	30.79
Polyester	218	35.33
Polyester/Cocona	209	33.87

Table 37. PMC Shirt Study Exercise Periods by Shirt Treatment		
Shirt Treatment	**Frequency**	**Percent**
Bio-Protect 500	297	48.14
Untreated	320	51.86

Table 38. PMC Shirt Study Shirts Worn by Gender		
Sex	**Frequency**	**Percent**
Female	39	47.56
Male	43	52.44

Table 39. PMC Shirt Study Shirts Worn by Shirt Fabric		
Shirt Fabric	**Frequency**	**Percent**
Modacrylic	20	24.39
Polyester	34	41.46
Polyester/Cocona	28	34.15

Table 40. PMC Shirt Study Shirts Worn by Shirt Treatment		
Shirt Treatment	**Frequency**	**Percent**
Bio-Protect 500	40	48.78
Untreated	42	51.22

Table 41. PMC Shirt Study Exercise Hours by Gender							
Sex	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**	**Total Shirts**	**Average Hours per Shirt**
Female	173.22	4.10	11.55	205	0.84	39	4.44
Male	353.17	4.92	14.13	412	0.86	43	8.21

Table 42. PMC Shirt Study Exercise Hours by Shirt Fabric							
Shirt Fabric	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**	**Total Shirts**	**Average Hours per Shirt**
Modacrylic	162.75	5.11	13.56	190	0.86	20	8.14
Polyester	175.35	4.06	11.69	218	0.80	34	5.16
Polyester/Cocona	188.28	5.02	14.48	209	0.90	28	6.72

Table 43. PMC Shirt Study Exercise Hours by Shirt Treatment							
Shirt Treatment	**Total Hours**	**Standard Deviation (hours)**	**Average Hours per Participant**	**Total Periods**	**Average Hours per Period**	**Total Shirts**	**Average Hours per Shirt**
Bio-Protect 500	257.42	3.52	12.87	297	0.87	40	6.44
Untreated	268.97	5.80	13.45	320	0.84	42	6.40

4.3 Summary of Shorts Usage

For the CP shorts study, the summary of study participation by gender, shorts fabric, shorts construction, and shorts treatment is displayed in Table 44, Table 45, Table 46, and Table 47. The numbers of exercise periods and the numbers of shorts worn by gender, shirt fabric, shorts construction, and shorts treatment are displayed in Table 48, Table 49, Table 50, Table 51, Table 52, Table 53, Table 54, and Table 55. Total exercise hours, standard deviation of total exercise hours, and average exercise hours by participant, by period, and by number of shorts worn for gender, shorts fabric, shorts construction, and shorts treatment are displayed in Table 56, Table 57, Table 58, and Table 59.

Some individuals may have participated twice. They were given new participant identification numbers for their second participation and are counted twice in the summaries below.

Table 44. CP Shorts Study Participation by Gender		
Sex	**Frequency**	**Percent**
Female	30	42.86
Male	40	57.14

Table 45. CP Shorts Study Participation by Shorts Fabric		
Shorts Fabric	**Frequency**	**Percent**
Cotton	31	44.29
Polyester	39	55.71

Table 46. CP Shorts Study Participation by Shorts Construction		
Shorts Construction	**Frequency**	**Percent**
Knitted	37	52.86
Woven	33	47.14

Table 47. CP Shorts Study Participation by Shorts Treatment		
Shorts Treatment	**Frequency**	**Percent**
Bio-Protect 500	34	48.57
Untreated	36	51.43

Table 48. CP Shorts Study Exercise Periods by Gender		
Sex	**Frequency**	**Percent**
Female	417	40.13
Male	622	59.87

Table 49. CP Shorts Study Exercise Periods by Shorts Fabric		
Shorts Fabric	**Frequency**	**Percent**
Cotton	448	43.12
Polyester	591	56.88

Table 50. CP Shorts Study Exercise Periods by Shorts Construction		
Shorts Construction	**Frequency**	**Percent**
Knitted	502	48.32
Woven	537	51.68

Table 51. CP Shorts Study Exercise Periods by Shorts Treatment		
Shorts Treatment	**Frequency**	**Percent**
Bio-Protect 500	490	47.16
Untreated	549	52.84

Table 52. CP Shorts Study Shorts Worn by Gender		
Sex	**Frequency**	**Percent**
Female	59	47.58
Male	65	52.42

Table 53. CP Shorts Study Shorts Worn by Shorts Fabric		
Shorts Fabric	**Frequency**	**Percent**
Cotton	63	50.81
Polyester	61	49.19

Table 54. CP Shorts Study Shorts Worn by Shorts Construction		
Shorts Construction	**Frequency**	**Percent**
Knitted	68	54.84
Woven	56	45.16

Table 55. CP Shorts Study Shorts Worn by Shorts Treatment		
Shorts Treatment	**Frequency**	**Percent**
Bio-Protect 500	60	48.39
Untreated	64	51.61

Table 56. CP Shorts Study Exercise Hours by Gender

Sex	Total Hours	Standard Deviation (hours)	Average Hours per Participant	Total Periods	Average Hours per Period	Total Shorts	Average Hours per Shorts
Female	350.27	3.12	11.68	417	0.84	59	5.94
Male	531.45	4.95	13.29	622	0.85	65	8.18

Table 57. CP Shorts Study Exercise Hours by Shorts Fabric

Shorts Fabric	Total Hours	Standard Deviation (hours)	Average Hours per Participant	Total Periods	Average Hours per Period	Total Shorts	Average Hours per Shorts
Cotton	393.88	3.08	12.71	448	0.88	63	6.25
Polyester	487.83	5.12	12.51	591	0.83	61	8.00

Table 58. CP Shorts Study Exercise Hours by Shorts Construction

Shorts Construction	Total Hours	Standard Deviation (hours)	Average Hours per Participant	Total Periods	Average Hours per Period	Total Shorts	Average Hours per Shorts
Knitted	432.58	5.03	11.69	502	0.86	68	6.36
Woven	449.13	3.10	13.61	537	0.84	56	8.02

Table 59. CP Shorts Study Exercise Hours by Shorts Treatment

Shorts Treatment	Total Hours	Standard Deviation (hours)	Average Hours per Participant	Total Periods	Average Hours per Period	Total Shorts	Average Hours per Shorts
Bio-Protect 500	409.30	3.94	12.04	490	0.84	60	6.82
Untreated	472.42	4.63	13.12	549	0.86	64	7.38

4.4 Shirt Length of Wear

The primary objective of the CPW and PMC shirt studies is to determine shirt length of wear, that is, the probability distribution of the useful life of shirts of different types with different treatments. Three main topics will be covered in this section, namely, the right-censoring of wear times (defined below), the results of life-test regressions of each shirt study, and the results of life-test regressions of the combined data from both shirt studies.

4.4.1 Censoring Issues

When a study participant decides that he has come to the end of his participation, his shirt has not come to the end of its useful life. Rather, the end of the shirt's useful life lies at some point in the future. The observed lifetime of the shirt is less than the useful life, and the observed lifetime is said to be censored from the right, or right censored. The statistical analysis should take censoring into account unless there is a compelling argument for ignoring censoring. However, if the fraction of observations that are censored is too high, usually something more than 10% of the observations, then the numerical analysis often fails. For this reason, it is necessary to examine the number and characteristics of censored observations and to compare them with the uncensored observations.

For the CPW shirt study, there were 103 shirts worn, of which 61 had censored lifetimes and 42 had uncensored lifetimes. The plot below in Figure 7 compares the empirical cumulative probability distributions of uncensored lifetimes in the blue solid line and censored lifetimes in the red dashed line. The distributions depart from each other for the censored lifetimes that exceed approximately 800 minutes of total wear. Figure 8 below compares the distributions of uncensored and censored shirt lifetimes, where shirts with censored lifetimes worn for 800 minutes or more have been excluded. Eleven shirts were excluded out of the total of 103 shirts, about 11% of the shirts, which does not seem to be an excessively large fraction of the study shirts. The large sample Kolmogorov-Smirnov test with a significant level equal to 21.51% indicates that there is no statistically significant difference at the 5% level between the distributions of the uncensored shirt lifetimes and the distribution of the reduced set of censored shirt lifetimes.

Since the distributions of the uncensored lifetimes and of the reduced set of censored lifetimes are statistically the same, the reduced set of censored lifetimes can be treated as if it were a set of uncensored lifetimes. The observed lifetimes of each shirt are assumed to be statistically independent. Thus, the joint distribution of the observed lifetimes is the product distribution, that is, the product of the distributions of each of the individual observed lifetimes. When the joint distribution is viewed as a function of the parameters to be estimated for given observed lifetimes, the joint distribution is called the likelihood function. The likelihood function is used for estimating the parameters for computing statistics whose observed significance levels, or p-values, are used for statistical significance tests. For an uncensored lifetime, the individual distribution of lifetime is just the probability density function. For a censored lifetime, the individual distribution of lifetime would be the survival probability function. However, the probability density function is being used in place of the survival probability function because the distribution of the set of censored lifetimes does not differ statistically from the distribution of the set of uncensored lifetimes.

Because of the argument in the foregoing paragraph, the reduced set of censored lifetimes can be combined with the uncensored lifetimes, and the combined set can be analyzed as if it consisted entirely of uncensored lifetimes. This solves the numerical analysis problem of having too high a fraction of censored observations. There are consequences of excluding shirts worn for 800 minutes or more from the analysis of the study. Given the average exercise time of 50 minutes, some number of shirts worn for 16 or more exercise sessions may be excluded. Conclusions from the study will not apply to such excessively long shirt lifetimes. However, conclusions will be in accord with the number of exercise sessions for each participant initially planned for the study, namely, 15 sessions.

Figure 7. Observed Lifetimes of CPW Shirts

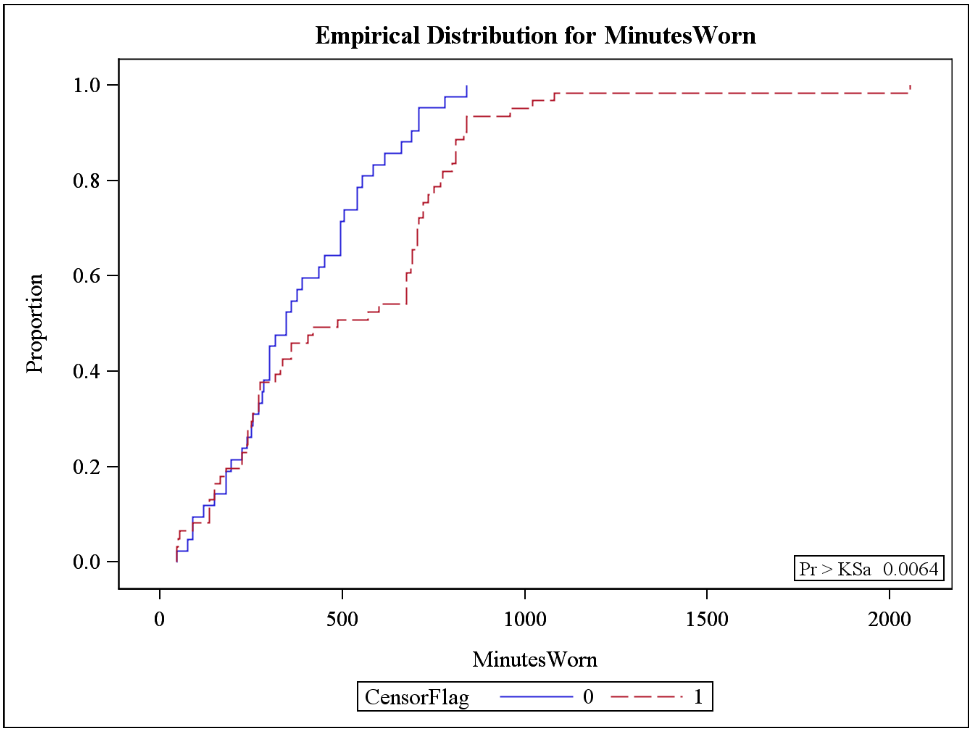
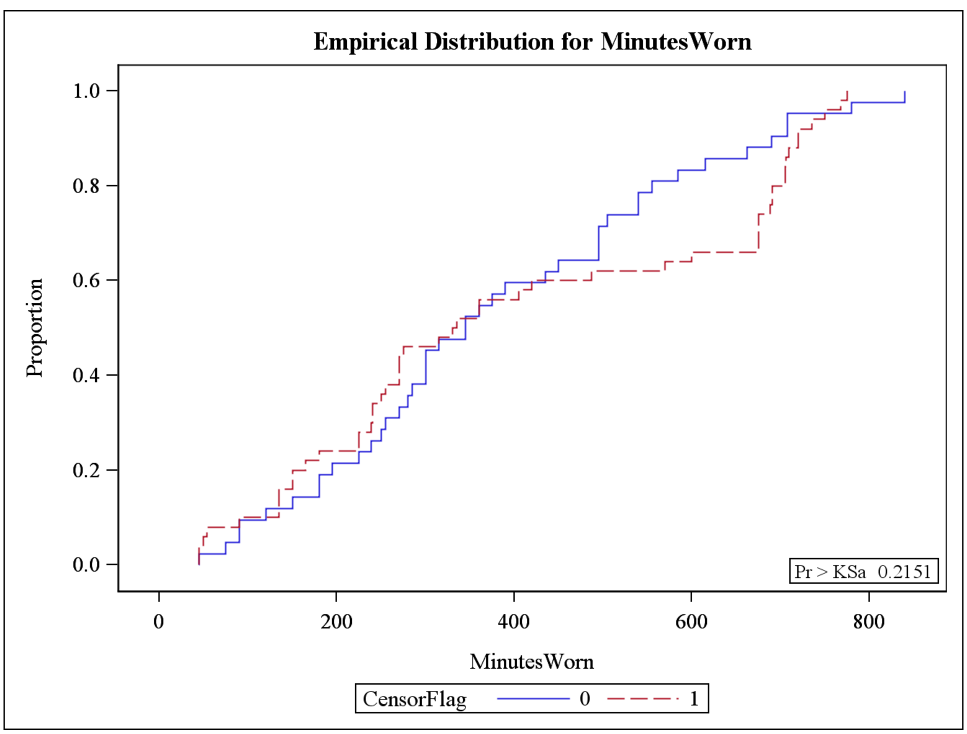


Figure 8. Edited Observed Lifetimes of CPW Shirts



For the PMC shirt study, there were 82 shirts worn, of which 40 had censored lifetimes and 42 had uncensored lifetimes. The plot below in Figure 9 compares the empirical cumulative probability distributions of uncensored lifetimes in the blue solid line and censored lifetimes in the red dashed line. The distributions depart from each other for the censored lifetimes that exceed approximately 800 minutes of total wear. Figure 10 below compares the distributions of uncensored and censored shirt lifetimes, where shirts with censored lifetimes worn for 800 minutes or more have been excluded. Six shirts were excluded out of the total of 82 shirts, about 7% of the shirts, which does not seem to be an excessively large fraction of the study shirts. The large sample Kolmogorov-Smirnov test with a significant level equal to 11.44% indicates that there is no statistically significant difference at the 5% level between the distributions of the uncensored shirt lifetimes and the distribution of the reduced set of censored shirt lifetimes.

The very same argument that applies above to the CPW shirt lifetimes also applies here to the PMC shirt lifetimes. Since the distributions are statistically the same, the reduced set of censored lifetimes can be treated as if they were uncensored lifetimes. The reduced set of censored lifetimes can be combined with the uncensored lifetimes, and the combined set can be analyzed as if it consisted entirely of uncensored lifetimes. This solves the numerical analysis problem of having too high a fraction of censored observations. There are consequences of excluding shirts worn for 800 minutes or more from the analysis of the study. Given the average exercise time of 50 minutes, some number of shirts worn for 16 or more exercise sessions may be excluded. Conclusions from the study will not apply to such excessively long shirt lifetimes. However, conclusions will be in accord with the number of exercise sessions for each participant initially planned for the study, namely, 15 sessions.

Figure 9. Observed Lifetimes of PMC Shirts

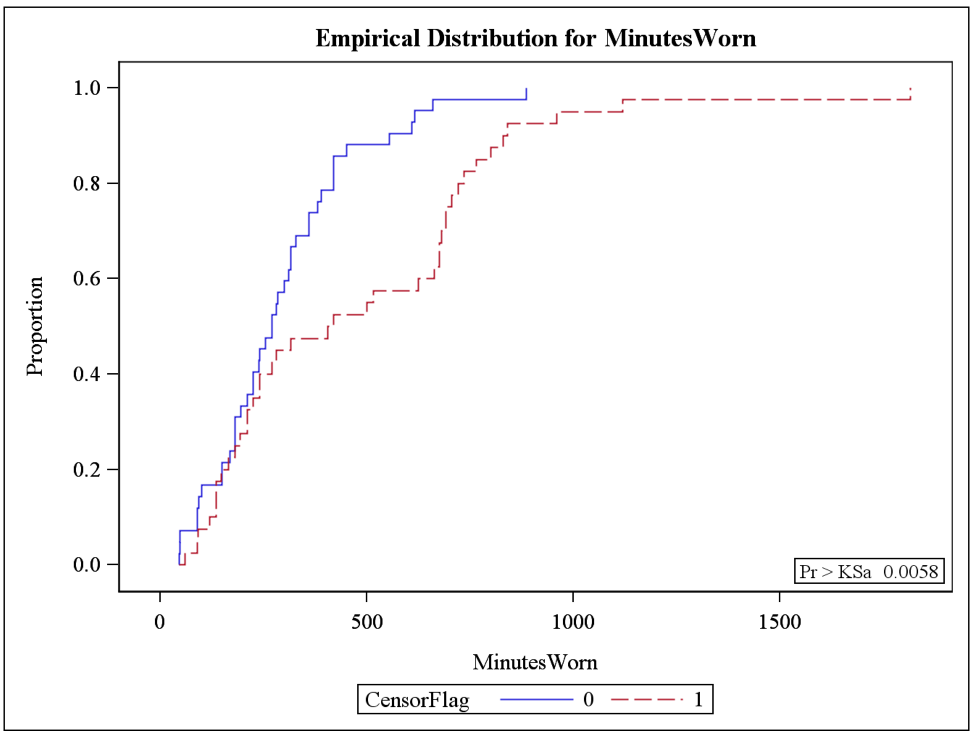
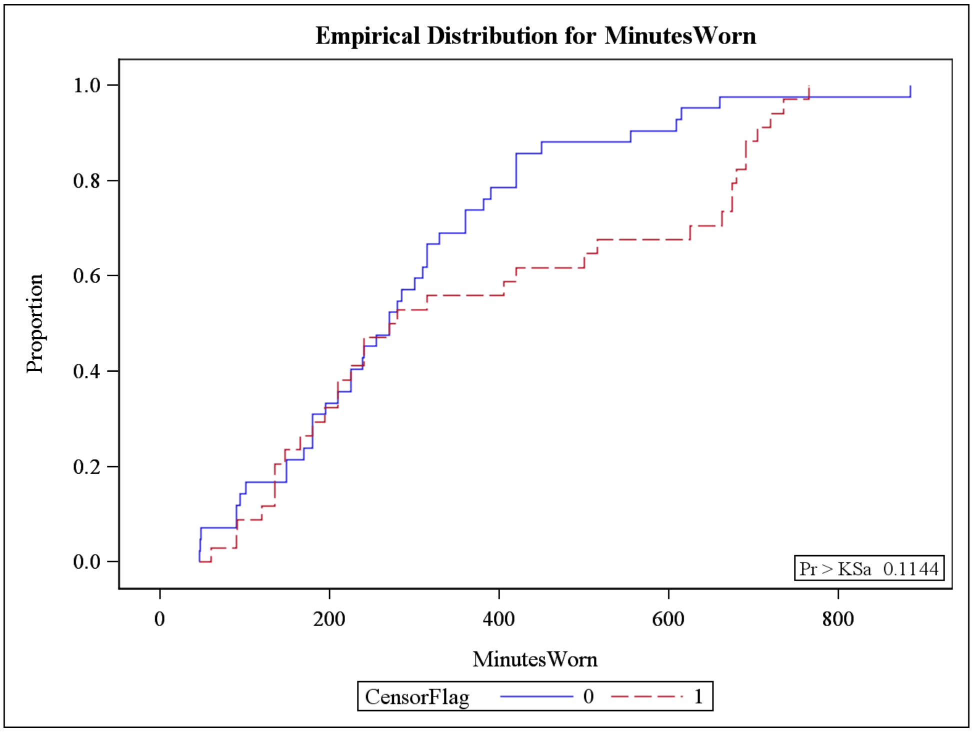


Figure 10. Edited Observed Lifetimes of PMC Shirts



For the combined CPW and PMC shirt studies, there were 162 shirts worn, of which 91 had censored lifetimes and 71 had uncensored lifetimes. The plot below in Figure 11 compares the empirical cumulative probability distributions of uncensored lifetimes in the blue solid line and censored lifetimes in the red dashed line. The distributions depart from each other for the censored lifetimes that exceed approximately 800 minutes of total wear. Figure 12 below compares the distributions of uncensored and censored shirt lifetimes, where shirts with censored lifetimes worn for 800 minutes or more have been excluded. Seventeen shirts were excluded out of the total of 162 shirts, about 10% of the shirts, which does not seem to be an excessively large fraction of the study shirts. The large sample Kolmogorov-Smirnov test with a significant level equal to 4.89% indicates that there is a marginal statistically significant difference at the 5% level between the distributions of the uncensored shirt lifetimes and the distribution of the reduced set of censored shirt lifetimes. However, an examination of the plot indicates an agreement comparable to that seen in Figure 8 and Figure 10. The marginal statistically significant difference can be attributed to the larger sample size of 145 versus the sample sizes of 92 and 76 in Figure 8 and Figure 10.

The very same argument that applies above to the CPW and PMC shirt lifetimes also applies here to the combined CPW and PMC shirt lifetimes. Since the distributions are close, the reduced set of censored lifetimes can be treated as if they were uncensored lifetimes. The reduced set of censored lifetimes can be combined with the uncensored lifetimes, and the combined set can be analyzed as if it consisted entirely of uncensored lifetimes. This solves the numerical analysis problem of having too high a fraction of censored observations. There are consequences of excluding shirts worn for 800 minutes or more from the analysis of the study. Given the average exercise time of 50 minutes, some number of shirts worn for 16 or more exercise sessions may be excluded. Conclusions from the study will not apply to such excessively long shirt lifetimes. However, conclusions will be in accord with the number of exercise sessions for each participant initially planned for the study, namely, 15 sessions.

Figure 11. Observed Lifetimes of CPW and PMC Shirts

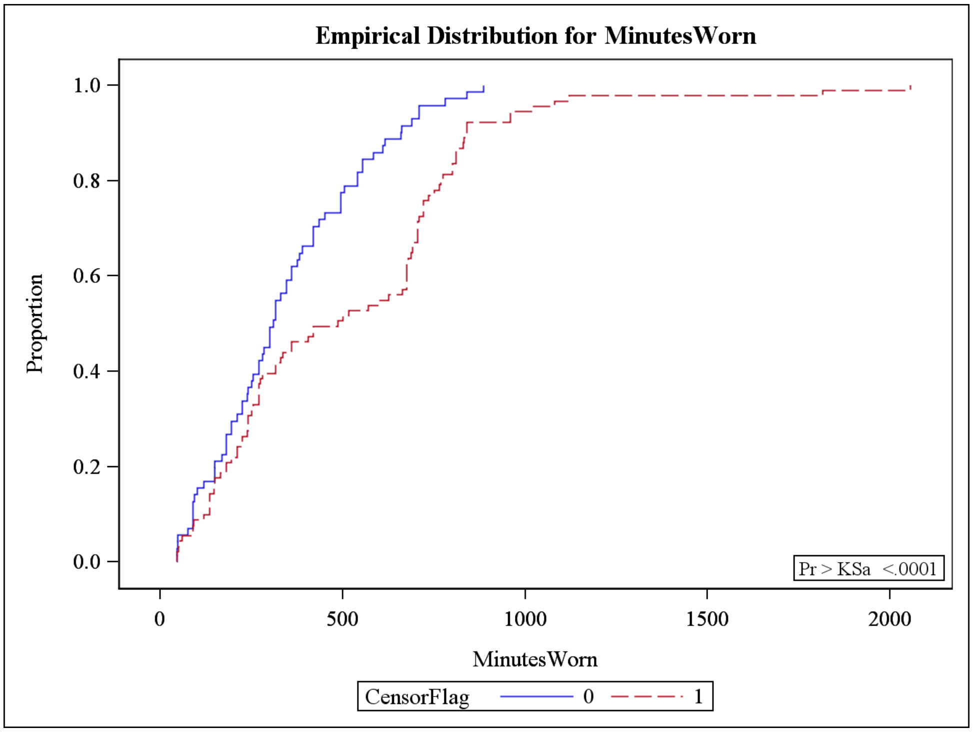
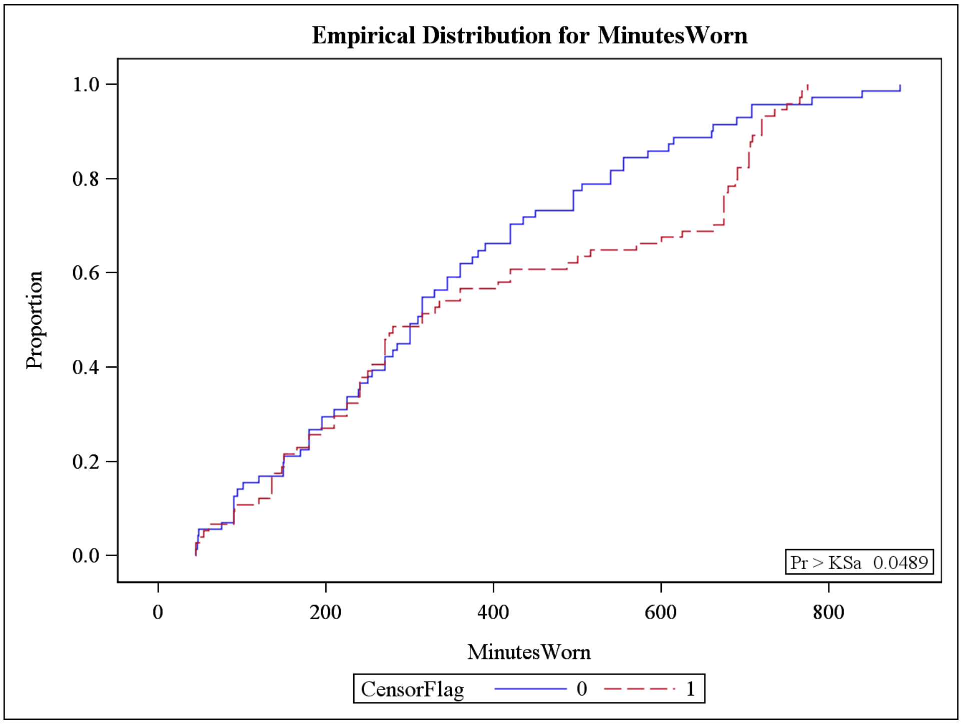


Figure 12. Edited Observed Lifetimes of CPW and PMC Shirts



4.4.2 Life-Test Regressions

Before considering the analysis of the combined CPW and PMC shirt data, each shirt study will be examined separately. Only the edited data will be used, excluding shirts worn 800 minutes or more, and all observed lifetimes will be treated as if they are not censored. An effects model was used that explains the observed lifetimes as the sum of terms due to an overall mean, fabric type, knit type, treatment type, and combinations of these types. For the PMC shirts, there was only one knit type (tight), and so knit type is not included in the analysis of the PMC shirts. An excellent fit to the data was found when the error had a Weibull distribution.

For the edited lifetimes of the CPW shirt study, Table 60 indicates that the only main effect or interaction that has statistically significant differences among treatment combinations at the 5% significance level is the combination of Shirt Fabric by Shirt Treatment, with an observed significance level (p-Value) of 3.75%.

For reference, the estimated average minutes of wear for the various treatment combinations of Shirt Fabric by Shirt Knit by Shirt Treatment are displayed in Table 61, along with lower and upper 95% confidence limits.

The estimated average minutes of wear for the various treatment combinations of Shirt Fabric by Shirt Treatment are displayed in Table 62, along with lower and upper 95% confidence limits. The three longest mean lifetimes are possessed by untreated wool (608 minutes), treated cotton (530 minutes), and treated polyester (469 minutes).

The particular treatment combinations with differences in mean lifetimes statistically significant at the 5% level are marked with an asterisk (*) in the right column of Table 63. The additional 201 minutes of mean lifetime for treated cotton compared to untreated cotton is indicative of the adherence and effectiveness of Bio-Protect 500 on cotton. The combination of Bio-Protect 500 with polyester produces a significant increase in mean lifetime compared to that of untreated cotton by 141 minutes. Finally, untreated wool has a significantly longer mean lifetime than untreated cotton by 280 minutes. Treating wool with Bio-Protect 500 seems to have an adverse effect on its mean lifetime.

A Weibull probability plot of the estimated residuals from the effects model is displayed in Figure 13 and shows a good fit to the Weibull distribution, with most of the estimated residuals lying within the 95% confidence band.

Table 60. CPW Shirt Study Weibull ANOVA
Type III Analysis of Effects

Effect	DF	Wald Chi-Square	p-Value (Pr > ChiSq)
ShirtFabric	2	2.6238	0.2693
ShirtKnit	1	0.1474	0.7010
ShirtFabric by ShirtKnit	2	2.4618	0.2920
ShirtTreatment	1	0.8239	0.3640
ShirtFabric by ShirtTreatment	2	6.5678	0.0375
ShirtKnit by ShirtTreatment	1	0.3894	0.5326
ShirtFabric by ShirtKnit by ShirtTreatment	2	1.2309	0.5404

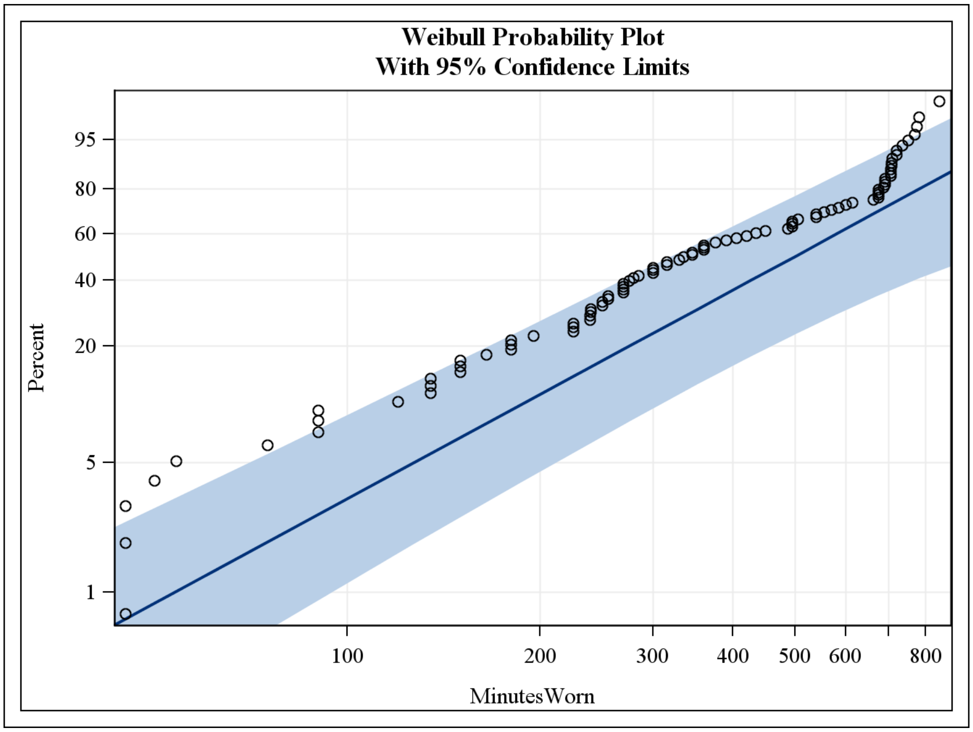
Table 61. CPW Shirt Fabric by Shirt Knit by Shirt Treatment Least Squares Means					
Shirt Fabric	**Shirt Knit**	**Shirt Treatment**	**Estimated Minutes**	**Lower 95% C. L. (minutes)**	**Upper 95% C. L. (minutes)**
Cotton	Open	Bio-Protect 500	501	348	722
Cotton	Open	Untreated	282	204	391
Cotton	Tight	Bio-Protect 500	560	389	807
Cotton	Tight	Untreated	382	286	511
Polyester	Open	Bio-Protect 500	477	323	707
Polyester	Open	Untreated	500	275	908
Polyester	Tight	Bio-Protect 500	462	332	641
Polyester	Tight	Untreated	339	254	453
Wool	Open	Bio-Protect 500	399	251	633
Wool	Open	Untreated	609	363	1021
Wool	Tight	Bio-Protect 500	533	336	847
Wool	Tight	Untreated	608	383	965

Table 62. CPW Shirt Fabric by Shirt Treatment Least Squares Means				
Shirt Fabric	**Shirt Treatment**	**Estimated Minutes**	**Lower 95% C. L. (minutes)**	**Upper 95% C. L. (minutes)**
Cotton	Bio-Protect 500	530	409	686
Cotton	Untreated	328	263	410
Polyester	Bio-Protect 500	469	363	607
Polyester	Untreated	412	296	574
Wool	Bio-Protect 500	461	333	640
Wool	Untreated	608	430	861

Table 63. Differences of CPW Shirt Fabric by Shirt Treatment Least Squares Means

Shirt Fabric by Shirt Treatment		minus Shirt Fabric by Shirt Treatment		Estimated Difference (minutes)	p-Value (Pr > |z|)	Significant at 5%
Cotton	Bio-Protect 500	Cotton	Untreated	201	0.0056	*
Cotton	Bio-Protect 500	Polyester	Bio-Protect 500	60	0.5147	
Cotton	Bio-Protect 500	Polyester	Untreated	118	0.24	
Cotton	Bio-Protect 500	Wool	Bio-Protect 500	68	0.5146	
Cotton	Bio-Protect 500	Wool	Untreated	-79	0.5301	
Cotton	Untreated	Polyester	Bio-Protect 500	-141	0.0352	*
Cotton	Untreated	Polyester	Untreated	-84	0.2611	
Cotton	Untreated	Wool	Bio-Protect 500	-133	0.0899	
Cotton	Untreated	Wool	Untreated	-280	0.0031	*
Polyester	Bio-Protect 500	Polyester	Untreated	58	0.5387	
Polyester	Bio-Protect 500	Wool	Bio-Protect 500	8	0.933	
Polyester	Bio-Protect 500	Wool	Untreated	-139	0.2376	
Polyester	Untreated	Wool	Bio-Protect 500	-49	0.6333	
Polyester	Untreated	Wool	Untreated	-197	0.1105	
Wool	Bio-Protect 500	Wool	Untreated	-147	0.2544	

Figure 13. CPW Estimated Effects Model Residuals



For the edited lifetimes of the PMC shirt study, Table 64 indicates that no main effect or interaction has statistically significant differences among treatment combinations at the 5% significance level. There is therefore no justification to examine differences among levels of main effects or interactions.

For reference, the estimated average minutes of wear for the various treatment combinations of Shirt Fabric by Shirt Treatment are displayed in Table 65, along with lower and upper 95% confidence limits.

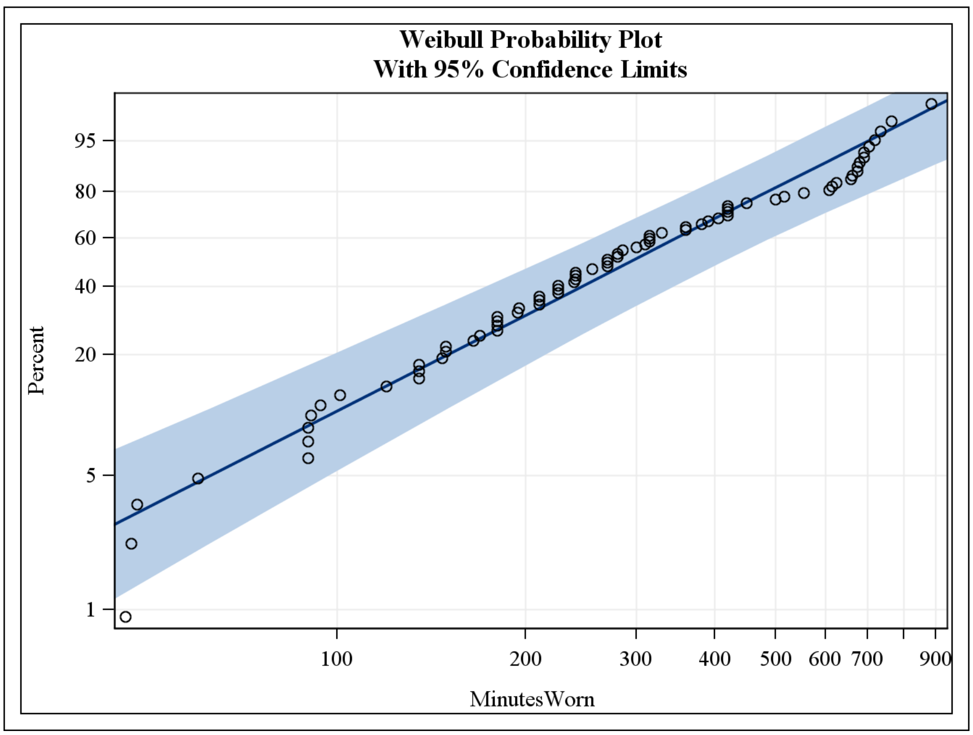
A Weibull probability plot of the estimated residuals from the effects model is displayed in Figure 14 and shows a good fit to the Weibull distribution, with most of the estimated residuals lying within the 95% confidence band.

Table 64. PMC Shirt Study Weibull ANOVA
Type III Analysis of Effects

Effect	DF	Wald Chi-Square	p-Value (Pr > ChiSq)
ShirtFabric	2	1.0546	0.5902
ShirtTreatment	1	0.4354	0.5093
ShirtFabric by ShirtTreatment	2	2.5937	0.2734

Table 65. PMC Shirt Fabric by Shirt Treatment Least Squares Means				
Shirt Fabric	**Shirt Treatment**	**Estimated Minutes**	**Lower 95% C. L. (minutes)**	**Upper 95% C. L. (minutes)**
Modacrylic	Bio-Protect 500	326	216	492
Modacrylic	Untreated	513	339	775
Polyester	Bio-Protect 500	357	268	476
Polyester	Untreated	332	250	440
Polyester/Cocona	Bio-Protect 500	403	283	574
Polyester/Cocona	Untreated	366	269	498

Figure 14. PWC Estimated Effects Model Residuals



4.4.3 Combined Analysis

For the combined edited lifetimes of the CPW and PMC shirt studies, Table 66 indicates that the only main effect or interaction that has almost statistically significant differences among treatment combinations at the 5% significance level is the combination of Shirt Fabric by Shirt Treatment, with an observed significance level (p-Value) of 5.10%.

The estimated average minutes of wear for the various treatment combinations of Shirt Fabric by Shirt Treatment are displayed in Table 67, along with lower and upper 95% confidence limits. The three longest mean lifetimes are possessed by untreated wool (600 minutes), treated cotton (526 minutes), and untreated modacrylic (515 minutes).

The particular treatment combinations with differences in mean lifetimes statistically significant at the 5% level are marked with an asterisk (*) in the right column of Table 68. The additional 199 minutes of mean lifetime for treated cotton compared to untreated cotton is indicative of the adherence and effectiveness of Bio-Protect 500 on cotton. The mean lifetime of untreated wool exceeds that of untreated cotton by 273 minutes. Similarly, the mean lifetime of untreated wool exceeds that of treated modacrylic by 274 minutes. Additionally, the mean lifetime of untreated wool exceeds that of untreated polyester by 240 minutes and that of untreated polyester/cocona, which is 95% polyester, by 237 minutes.

A Weibull probability plot of the estimated residuals from the effects model is displayed in Figure 15 and shows a good fit to the Weibull distribution, with most of the estimated residuals lying within the 95% confidence band.

Table 66. Combined CPW and PMC Shirt Studies Weibull ANOVA Type III Analysis of Effects

Effect	DF	Wald Chi-Square	p-Value (Pr > ChiSq)
ShirtFabric	4	4.7956	0.3089
ShirtTreatment	1	0.0109	0.9170
ShirtFabric by ShirtTreatment	4	9.4378	0.0510

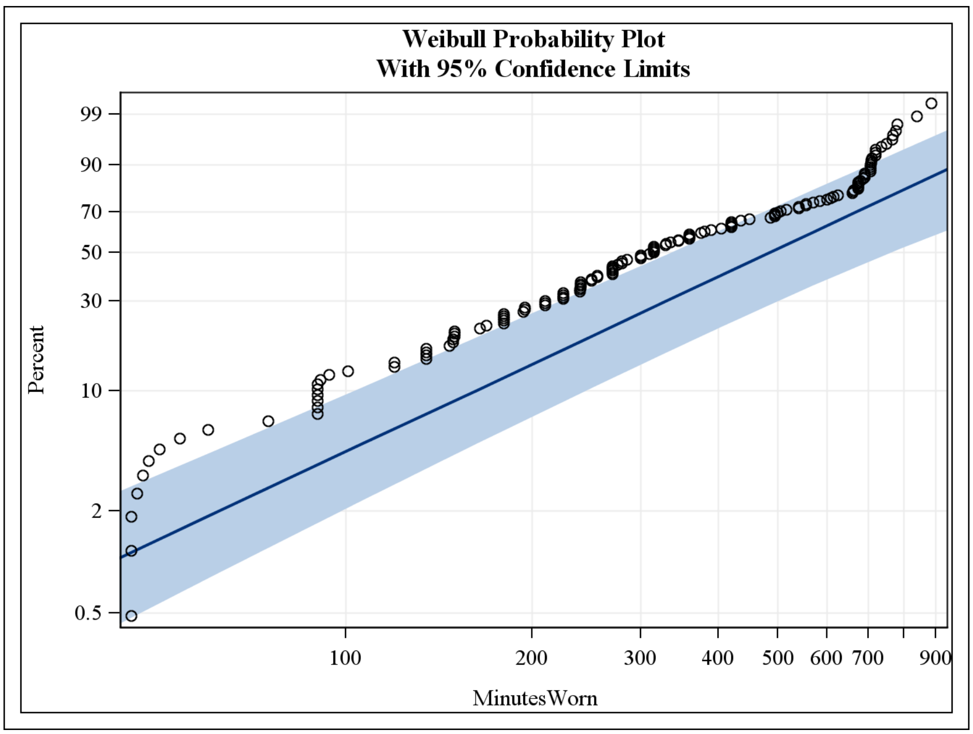
Table 67. Combined CPW and PMC Shirt Fabric by Shirt Treatment Least Squares Means

Shirt Fabric	Shirt Treatment	Estimated Minutes	Lower 95% C. L. (minutes)	Upper 95% C. L. (minutes)
Cotton	Bio-Protect 500	526	396	699
Cotton	Untreated	327	258	414
Modacrylic	Bio-Protect 500	327	218	489
Modacrylic	Untreated	515	344	771
Polyester	Bio-Protect 500	394	311	498
Polyester	Untreated	360	279	465
Polyester/Cocona	Bio-Protect 500	405	287	572
Polyester/Cocona	Untreated	369	274	498
Wool	Bio-Protect 500	465	324	666
Wool	Untreated	600	411	877

Table 68. Differences of Combined CPW and PMC Shirt Fabric by Shirt Treatment Least Squares Means						
Shirt Fabric by Shirt Treatment		**minus Shirt Fabric by Shirt Treatment**		**Estimated Difference (minutes)**	**p-Value (Pr > |z|)**	**Significant at 5%**
Cotton	Bio-Protect 500	Cotton	Untreated	199	0.0115	*
Cotton	Bio-Protect 500	Modacrylic	Bio-Protect 500	199	0.0579	
Cotton	Bio-Protect 500	Modacrylic	Untreated	11	0.9343	
Cotton	Bio-Protect 500	Polyester	Bio-Protect 500	132	0.1224	
Cotton	Bio-Protect 500	Polyester	Untreated	166	0.052	
Cotton	Bio-Protect 500	Polyester/Cocona	Bio-Protect 500	121	0.2509	
Cotton	Bio-Protect 500	Polyester/Cocona	Untreated	157	0.0913	
Cotton	Bio-Protect 500	Wool	Bio-Protect 500	61	0.5958	
Cotton	Bio-Protect 500	Wool	Untreated	-74	0.5856	
Cotton	Untreated	Modacrylic	Bio-Protect 500	0	0.9987	
Cotton	Untreated	Modacrylic	Untreated	-188	0.0549	
Cotton	Untreated	Polyester	Bio-Protect 500	-67	0.267	
Cotton	Untreated	Polyester	Untreated	-34	0.5791	
Cotton	Untreated	Polyester/Cocona	Bio-Protect 500	-78	0.3096	
Cotton	Untreated	Polyester/Cocona	Untreated	-43	0.5218	
Cotton	Untreated	Wool	Bio-Protect 500	-138	0.1082	
Cotton	Untreated	Wool	Untreated	-273	0.0075	*
Modacrylic	Bio-Protect 500	Modacrylic	Untreated	-189	0.1163	
Modacrylic	Bio-Protect 500	Polyester	Bio-Protect 500	-67	0.4317	
Modacrylic	Bio-Protect 500	Polyester	Untreated	-34	0.6859	
Modacrylic	Bio-Protect 500	Polyester/Cocona	Bio-Protect 500	-79	0.4245	
Modacrylic	Bio-Protect 500	Polyester/Cocona	Untreated	-43	0.6298	
Modacrylic	Bio-Protect 500	Wool	Bio-Protect 500	-138	0.2005	
Modacrylic	Bio-Protect 500	Wool	Untreated	-274	0.031	*
Modacrylic	Untreated	Polyester	Bio-Protect 500	122	0.2557	
Modacrylic	Untreated	Polyester	Untreated	155	0.1407	
Modacrylic	Untreated	Polyester/Cocona	Bio-Protect 500	110	0.3726	
Modacrylic	Untreated	Polyester/Cocona	Untreated	146	0.1905	
Modacrylic	Untreated	Wool	Bio-Protect 500	51	0.7073	
Modacrylic	Untreated	Wool	Untreated	-85	0.5885	
Polyester	Bio-Protect 500	Polyester	Untreated	33	0.6158	
Polyester	Bio-Protect 500	Polyester/Cocona	Bio-Protect 500	-12	0.8912	
Polyester	Bio-Protect 500	Polyester/Cocona	Untreated	24	0.7389	
Polyester	Bio-Protect 500	Wool	Bio-Protect 500	-71	0.448	

Table 68. Differences of Combined CPW and PMC Shirt Fabric by Shirt Treatment Least Squares Means						
Shirt Fabric by Shirt Treatment		**minus Shirt Fabric by Shirt Treatment**		**Estimated Difference (minutes)**	**p-Value (Pr > |z|)**	**Significant at 5%**
Polyester	Bio-Protect 500	Wool	Untreated	-207	0.0632	
Polyester	Untreated	Polyester/Cocona	Bio-Protect 500	-45	0.5906	
Polyester	Untreated	Polyester/Cocona	Untreated	-9	0.9017	
Polyester	Untreated	Wool	Bio-Protect 500	-104	0.258	
Polyester	Untreated	Wool	Untreated	-240	0.0285	*
Polyester/Cocona	Bio-Protect 500	Polyester/Cocona	Untreated	36	0.688	
Polyester/Cocona	Bio-Protect 500	Wool	Bio-Protect 500	-59	0.589	
Polyester/Cocona	Bio-Protect 500	Wool	Untreated	-195	0.132	
Polyester/Cocona	Untreated	Wool	Bio-Protect 500	-95	0.3338	
Polyester/Cocona	Untreated	Wool	Untreated	-231	0.0477	*
Wool	Bio-Protect 500	Wool	Untreated	-136	0.3371	

Figure 15. Combined CPW and PMC Estimated Effects Model Residuals



4.5 Shorts Length of Wear

The primary objective of the CP shorts study is to determine shorts length of wear, that is, the probability distribution of the useful life of shorts of different types with different treatments. Two main topics will be covered in this section, namely, the right-censoring of wear times and the results of life-test regressions of the data from the shorts study.

4.5.1 Censoring Issues

When a study participant decides that he has come to the end of his participation, his shorts have not come to the end of their useful life. Rather, the end of the shorts' useful life lies at some point in the future. The observed lifetime of the shorts is less than the useful life, and the observed lifetime is said to be censored from the right, or right censored. The statistical analysis should take censoring into account unless there is a compelling argument for ignoring censoring. However, if the fraction of observations that are censored is too high, usually something more than 10% of the observations, then the numerical analysis often fails. For this reason, it is necessary to examine the number and characteristics of censored observations and to compare them with the uncensored observations.

For the CP shorts study, there were 124 shorts worn, of which 70 had censored lifetimes and 54 had uncensored lifetimes. The plot below in Figure 16 compares the empirical cumulative probability distributions of uncensored lifetimes in the blue solid line and censored lifetimes in the red dashed line. The distributions depart from each other for the censored lifetimes that exceed approximately 800 minutes of total wear. Figure 17 below compares the distributions of uncensored and censored shirt lifetimes, where shirts with censored lifetimes worn for 800 minutes or more have been excluded. Eight shorts were excluded out of the total of 124 shorts, about 6% of the shirts, which does not seem to be an excessively large fraction of the study shirts. The large sample Kolmogorov-Smirnov test with a significant level equal to 5.02% indicates that there is no statistically significant difference at the 5% level between the distributions of the uncensored shorts lifetimes and the distribution of the reduced set of censored shorts lifetimes.

The very same argument that applies above to the shirt lifetimes also applies here to the CP shorts lifetimes. Since the distributions are statistically the same, the reduced set of censored lifetimes can be treated as if they were uncensored lifetimes. The reduced set of censored lifetimes can be combined with the uncensored lifetimes, and the combined set can be analyzed as if it consisted entirely of uncensored lifetimes. This solves the numerical analysis problem of having too high a fraction of censored observations. There are consequences of excluding shorts worn for 800 minutes or more from the analysis of the study. Given the average exercise time of 50 minutes, some number of shorts worn for 16 or more exercise sessions may be excluded. Conclusions from the study will not apply to such excessively long shorts lifetimes. However, conclusions will be in accord with the number of exercise sessions for each participant initially planned for the study, namely, 15 sessions.

Figure 16. Observed Lifetimes of CP Shorts

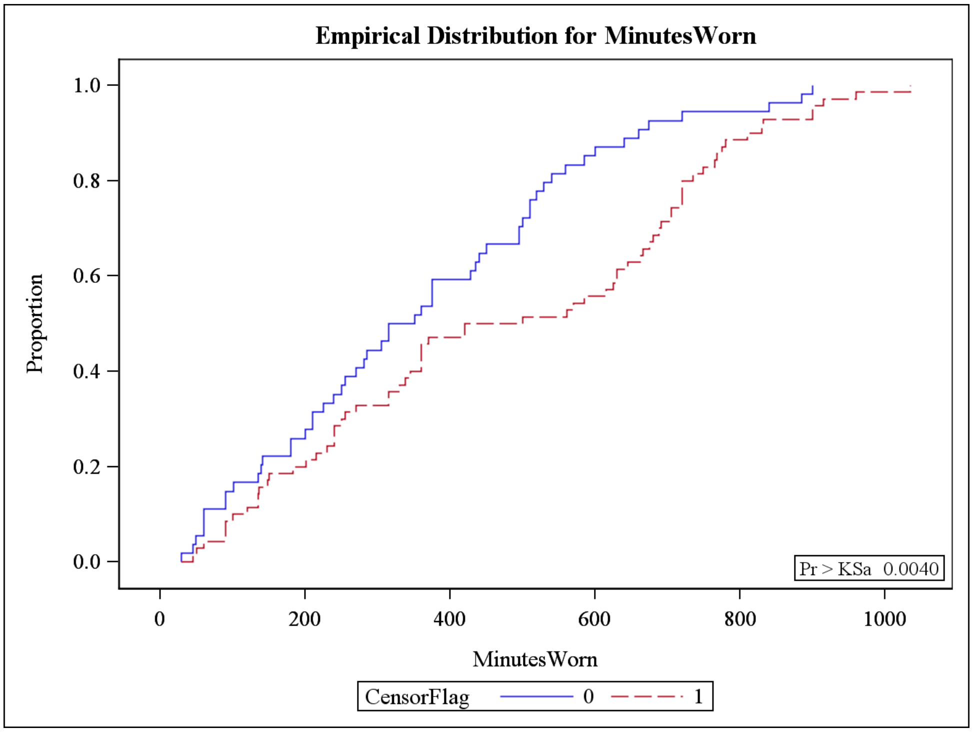
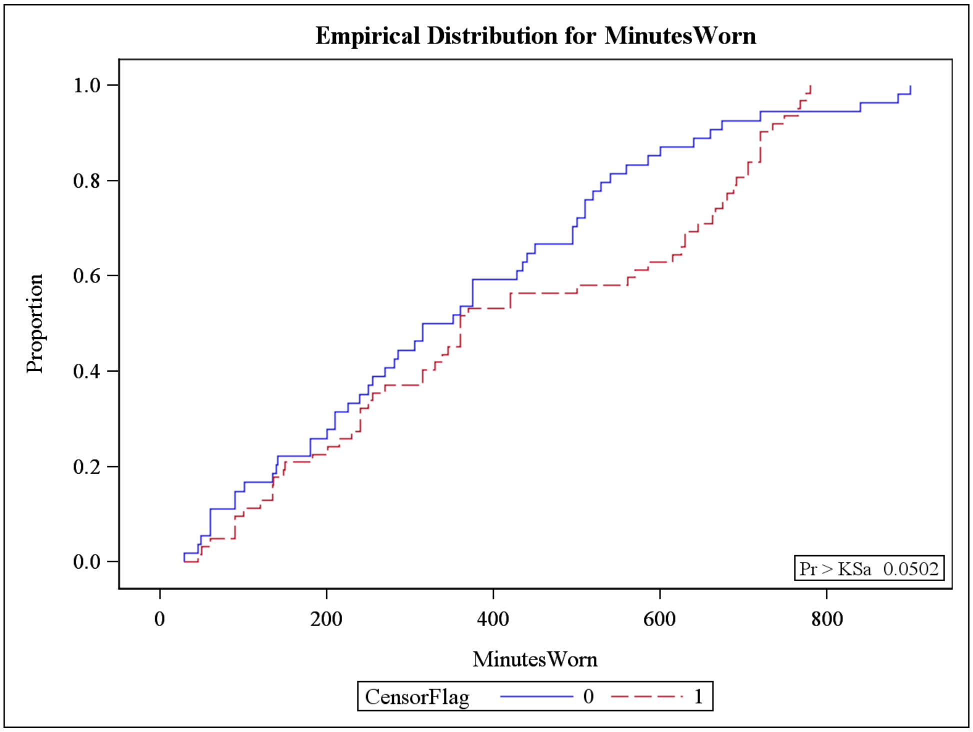


Figure 17. Edited Observed Lifetimes of CP Shorts



4.5.1 Life-Test Regression

In the analysis of the CP shorts data, only the edited data will be used, excluding shorts worn 800 minutes or more, and all observed lifetimes will be treated as if they are not censored. An effects model was used that explains the observed lifetimes as the sum of terms due to an overall mean, fabric type, fabric construction, treatment type, and combinations of these types. An excellent fit to the data was found when the error had a Weibull distribution.

For the edited lifetimes of the CP shorts study, Table 69 indicates that no main effect or interaction has statistically significant differences among treatment combinations at the 5% significance level. There is therefore no justification to examine differences among levels of main effects or interactions.

For reference, the estimated average minutes of wear for the various treatment combinations of CP Shorts Fabric by Shorts Construction by Shorts Treatment are displayed in Table 70, along with lower and upper 95% confidence limits.

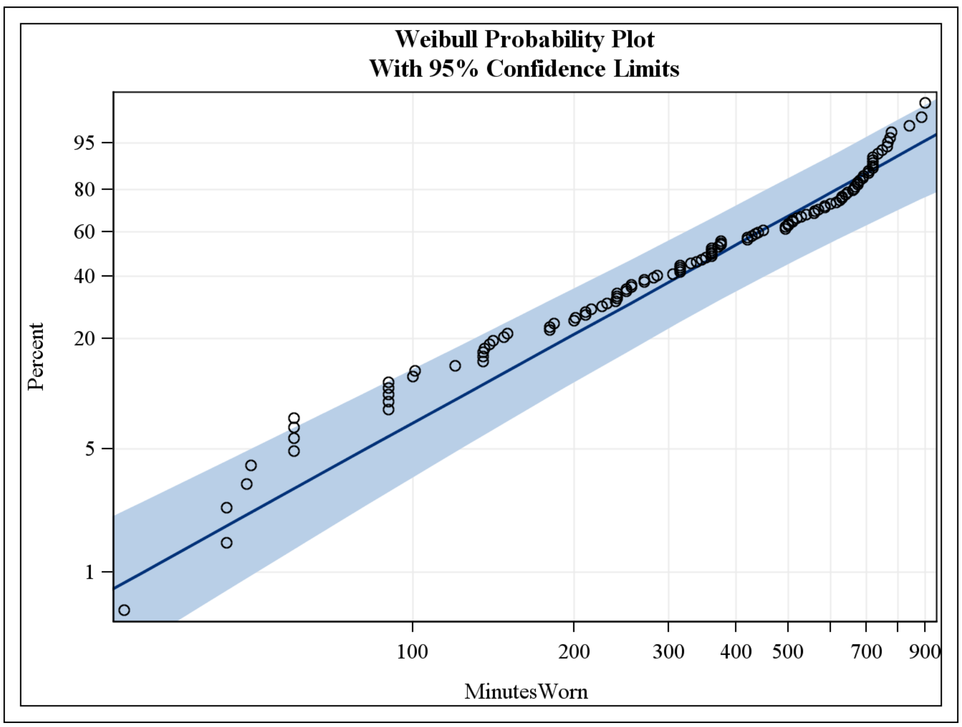
A Weibull probability plot of the estimated residuals from the effects model is displayed in Figure 18 and shows a good fit to the Weibull distribution, with most of the estimated residuals lying within the 95% confidence band.

Table 69. CP Shorts Study Weibull ANOVA
Type III Analysis of Effects

Effect	DF	Wald Chi-Square	p-Value (Pr > ChiSq)
ShortsFabric	1	1.8983	0.1683
ShortsConstruction	1	0.7591	0.3836
ShortsFabric * ShortsConstruction	1	1.0330	0.3094
ShortsTreatment	1	0.4393	0.5075
ShortsFabric* ShortsTreatment	1	0.0012	0.9728
ShortsConstruction * ShortsTreatment	1	0.4097	0.5221
ShortsFabric * ShortsConstruction * ShortsTreatment	1	0.5826	0.4453

Table 70. CP Shorts Fabric by Shorts Construction by Shorts Treatment Least Squares Means					
Shorts Fabric	**Shorts Construction**	**Shorts Treatment**	**Estimated Minutes**	**Lower 95% C. L. (minutes)**	**Upper 95% C. L. (minutes)**
Cotton	Knitted	Bio-Protect 500	356	278	457
Cotton	Knitted	Untreated	389	296	511
Cotton	Woven	Bio-Protect 500	517	353	759
Cotton	Woven	Untreated	411	295	572
Polyester	Knitted	Bio-Protect 500	511	355	736
Polyester	Knitted	Untreated	466	346	628
Polyester	Woven	Bio-Protect 500	496	378	651
Polyester	Woven	Untreated	465	333	648

Figure 18. CP Estimated Effects Model Residuals



4.6 Preference Analysis

The secondary objective of all three studies, the CPW and the PMC shirt studies and the CP shorts study, is to determine the preference to these garments according to the nine preference scales displayed in Table 12. Rather than looking at each of the nine scales separately and trying to interpret the balance of preferences of respondents with respect to these nine scales, it was decided for this report to aggregate the nine scales into one combined scale. This aggregation was achieved simply by summing up the responses in each participant's daily questionnaire separately for each of the five preference categories. For this summation, each selected preference category has the value 1 and the remaining unselected preference categories have the value 0. A daily questionnaire in which all the responses for the nine scales are in the same column will have a sharply defined result for the aggregated scale with a value of 9 for that preference category. Alternatively, if the responses to a daily questionnaire are distributed over various preference categories from scale to scale, then the result for the aggregated scale may not be sharply defined.

In order to achieve comparability with the length-of-wear analysis of Sections 4.4 and 4.5 for shirts and shorts, those garments that were worn for 800 minutes or more were excluded from the analysis of preferences.

In addition to computing an aggregated preference scale, it was decided for this report to combine the leftmost two preference categories in Table 12 into a single composite preference category called Favorable. Likewise, the rightmost two preference categories in Table 12 are combined into the composite category called Unfavorable. The center preference category remained as Neutral. The use of such composite categories provides for an easier interpretation of the results.

The values for two observational categorical variables, the Borg scale for perceived exertion and the number of days a shirt or shorts were worn, were also combined into composite levels in order to ease the process of interpreting the results. These combined ranges of values are displayed in Table 71 and Table 72.

Table 71. Combined Levels of Perceived Exertion

Borg Scale Values	6 through 12	13 through 16	17 through 20
BorgEffort Value	Light	Hard	Very Hard

Table 72. Combined Levels for Number of Days Garments Were Worn

Number of Days Worn	1 through 5	6 through 10	11 through 16
DaysWorn	1 to 5	6 to 10	11 to 16

4.7 Shirt Preferences

For the analysis of shirt preferences, the preference responses for just those shirts that were worn less than 800 minutes were used. This was done to provide comparability with the length-of-wear analysis in Section 4.4**.**

The proportions of aggregated responses in the categories Favorable, Neutral, and Unfavorable are displayed as bar graphs in Figure 19, Figure 20**,** Figure 21, and Figure 22 for the levels of the observational variables gender, perceived exertion, days worn and shirt characteristics for the combined CPW and PMC shirt studies. For comparability with the length-of-wear analysis in Table 67 and Table 68, where Shirt Fabric and Shirt Treatment were compared, Figure 23 displays the proportions of aggregated responses for which the data for the two types of knit, open and tight, have been combined under their respective combinations of fabric and treatment.

For each of the levels of the observational variables gender, perceived exertion, days worn and shirt characteristics, lower and upper 95% confidence levels are displayed in bar graphs for the proportion of aggregated Favorable responses in Figure 24, Figure 25, Figure 26, and Figure 27. It was decided to look with this detail at the aggregated Favorable proportion because the primary technical interest is in the favorable responses. For each level, the proportion is displayed in red in the central bar flanked on each side by a bar for the upper confidence limit in green and the lower confidence limit in blue.

A simple graphical method of determining if two proportions are approximately different statistically is to see if neither proportion lies between the confidence limits of the other proportion. In Figure 24, Aggregated Favorable Proportion by Gender for Edited CPW and PMC Shirt Studies, the proportion of aggregated favorable responses for male participants is about the same as that for female participants. The presence or absence of statistical significance should always be interpreted cautiously. A statistically significant difference may not be considered technically significant from the viewpoint of applications.

In Figure 25, Aggregated Favorable Proportion by Perceived Exertion for Edited CPW and PMC Shirt Studies, the proportion of responses in the Hard effort level is significantly different from that in the Light and the Very Hard levels, while the proportions of responses in the Light and Very Hard levels are not significantly different.

In Figure 26, Aggregated Favorable Proportion by Days Worn for Edited CPW and PMC Shirt Studies, the aggregated Favorable proportions decrease steadily and significantly as the number of Days Worn increases through 16 days, which is to be expected.

The aggregated Favorable proportions in Figure 27, Aggregated Favorable Proportion by Shirt Characteristics for Edited CPW and PMC Studies, are arranged from highest to lowest for easier interpretation of the results. The shirt types with the highest aggregated Favorable proportions fall into three groups, from higher to lower proportion:

1. Wool Untreated Open-Knit, Polyester Bio-Protect 500 Tight-Knit, and Polyester Bio-Protect 500 Open-Knit
2. Cotton Untreated Open-Knit, Polyester Untreated Tight-Knit, Cotton Untreated Tight-Knit, and Modacrylic Untreated (Tight-Knit)
3. Cotton Bio-Protect 500 Tight-Knit, and Polyester/Cocona Untreated (Tight-Knit)

In comparing Figure 27 with the results in Table 67, Combined CPW and PMC Shirt Fabric by Shirt Treatment Least Squares Means, it is seen that the most preferred material, Wool Untreated Open-Knit, contributes to the material that was worn the longest, Wool Untreated. For comparability to the length-of-wear analysis, Figure 28 displays the favorable proportion of aggregated responses for which the data for the two types of knit, open and tight, have been combined under their respective combinations of fabric and treatment. The much lower favorability of untreated wool in Figure 28 is due to the adverse favorability seen in Figure 27 for treated wool and untreated tight-knit wool.

The nine preference scales in Table 12 were tabulated to determine the preference responses at the end of the exercise period prior to the period when the old shirt was retired and a new shirt was started. The assumption is that an unfavorable assessment of the shirt leads to its retirement. There were two responses that were predominantly unfavorable before a new shirt was started, scent and dryness. These responses are evidence of an association between scent and dryness right after exercise and change of shirt in the next exercise period, and not evidence of causality. The tabulations for these responses are displayed in Table 73 and Table 74 and graphically in Figure 29 and Figure 30.

Figure 19. Aggregated Preference Proportions by Gender for Edited CPW and PMC Shirt Studies

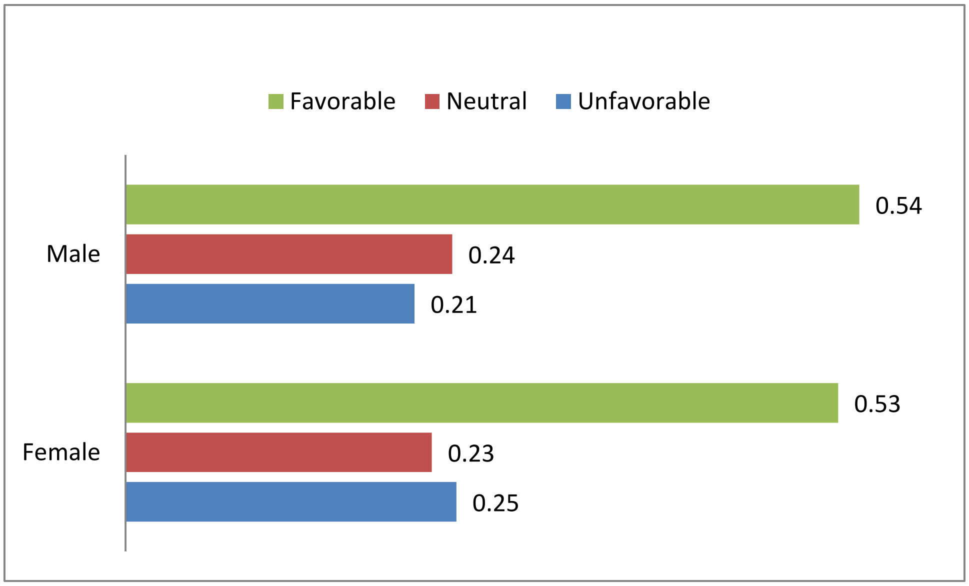


Figure 20. Aggregated Preference Proportions by Perceived Exertion for Edited CPW and PMC Shirt Studies

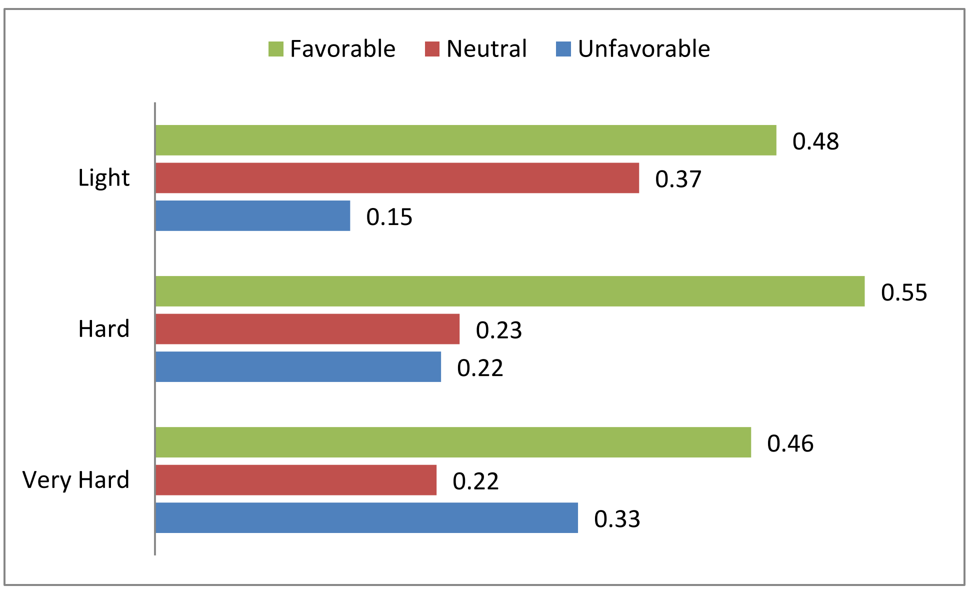


Figure 21. Aggregated Preference Proportions by Days Worn for Edited CPW and PMC Shirt Studies

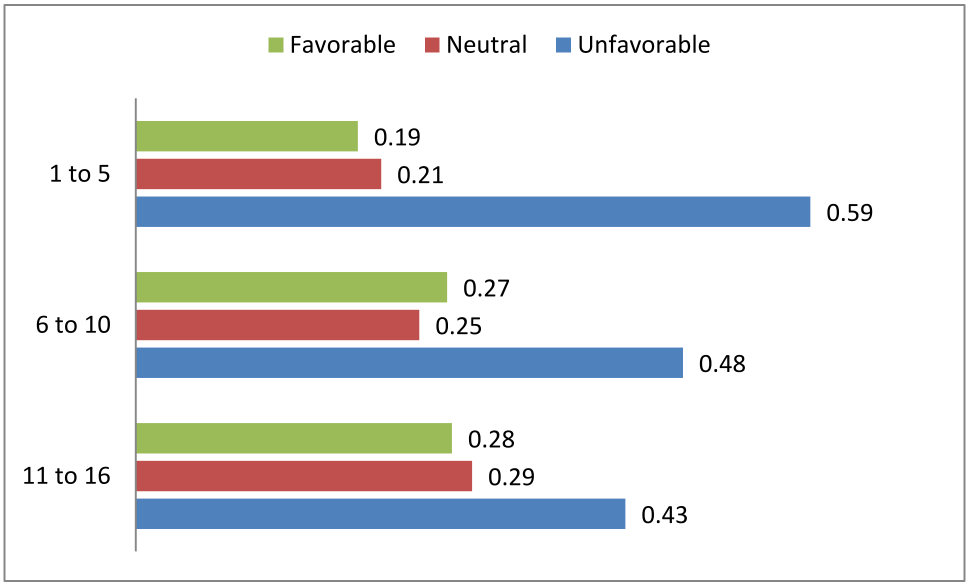


Figure 22. Aggregated Preference Proportions by Shirt Characteristics for Edited CPW and PMC Studies

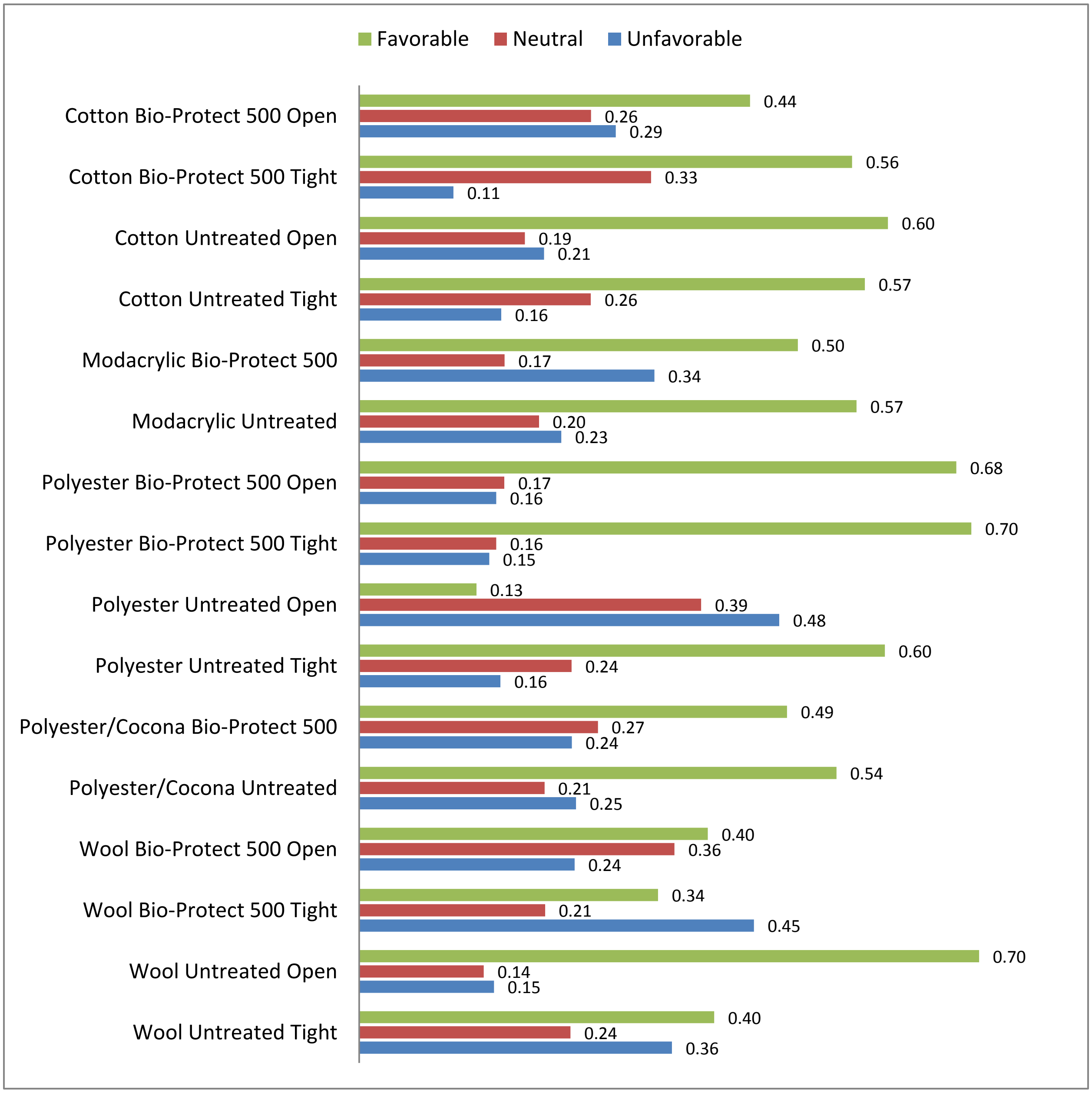


Figure 23. Aggregated Preference Proportions by Shirt Fabric and Shirt Treatment for Edited CPW and PMC Studies

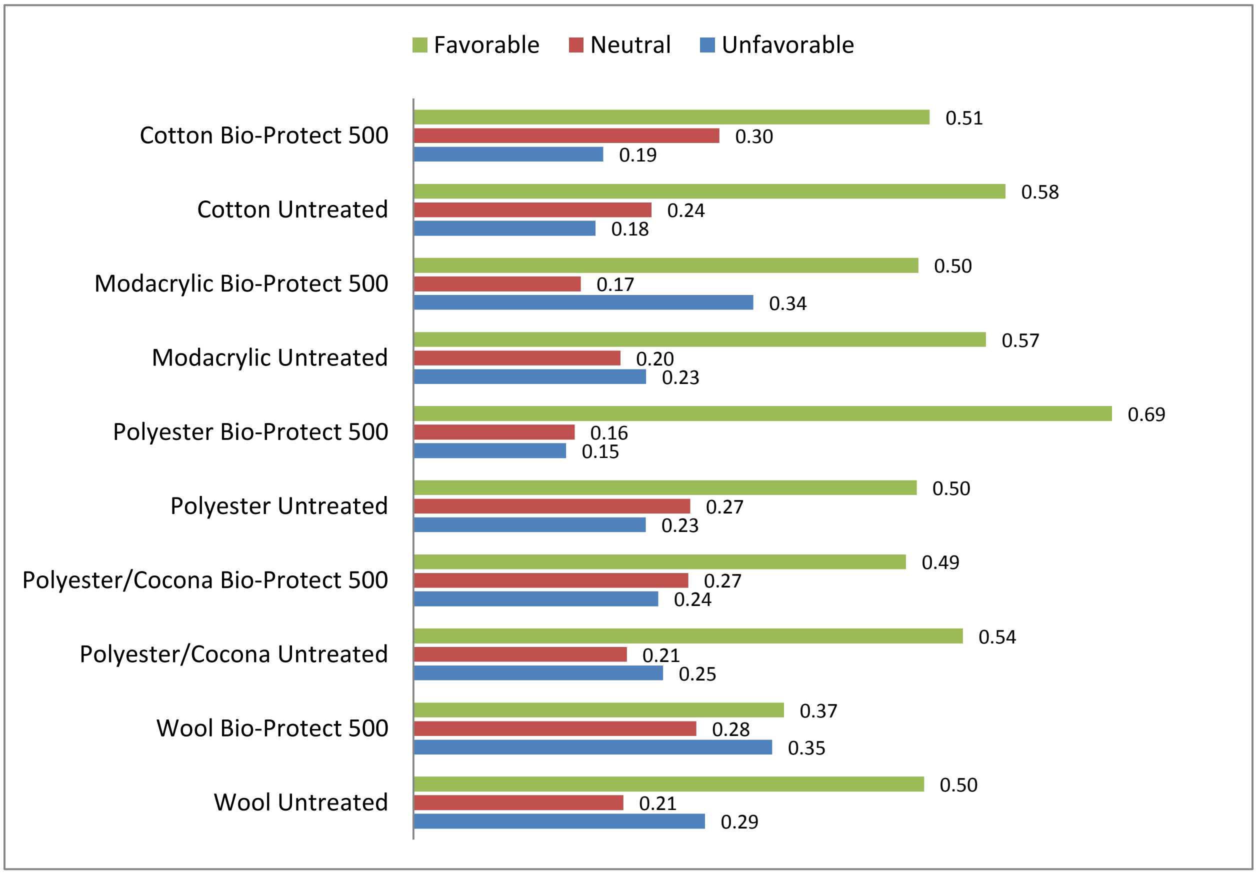


Figure 24. Aggregated Favorable Proportion by Gender for Edited CPW and PMC Shirt Studies

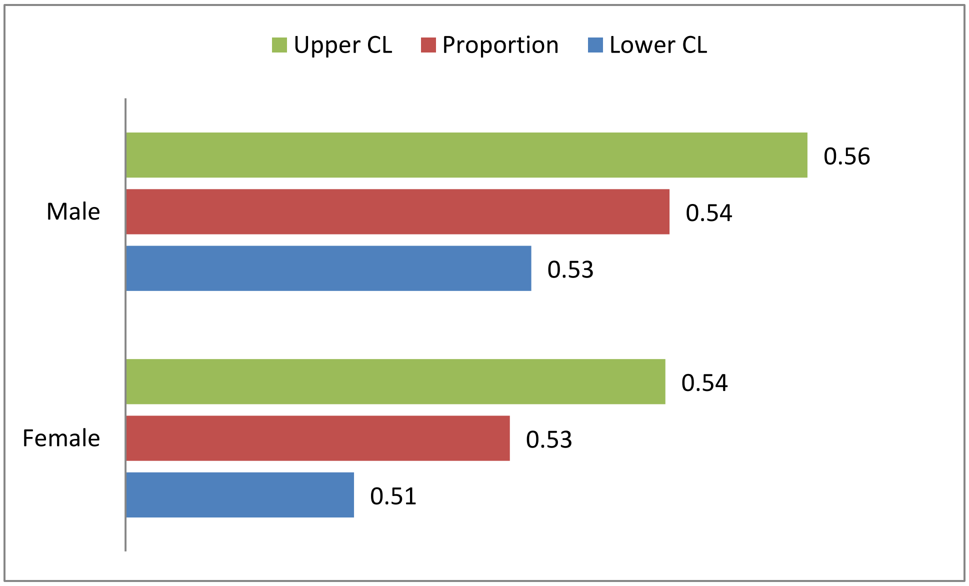


Figure 25. Aggregated Favorable Proportion by Perceived Exertion for CPW Edited and PMC Shirt Studies

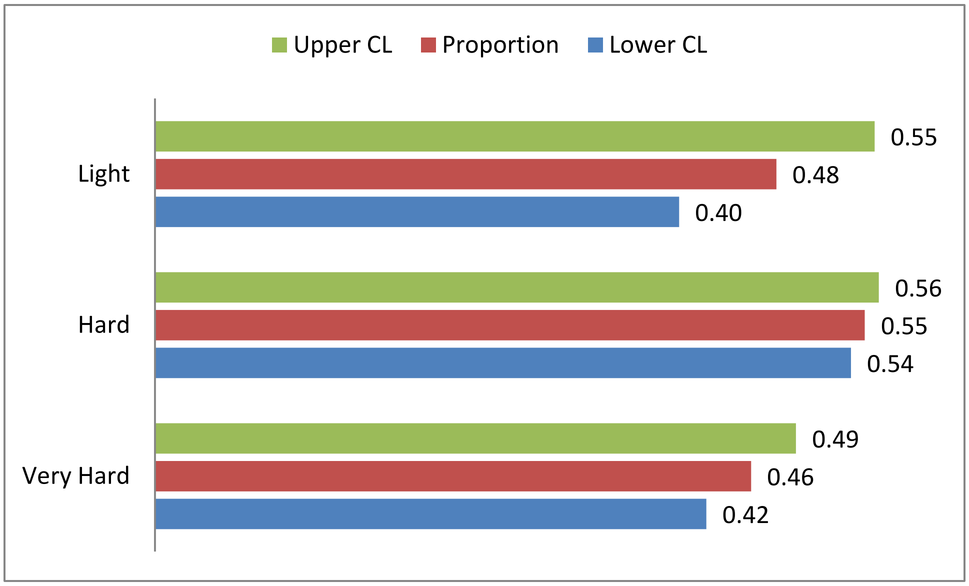


Figure 26. Aggregated Favorable Proportion by Days Worn for Edited CPW and PMC Shirt Studies

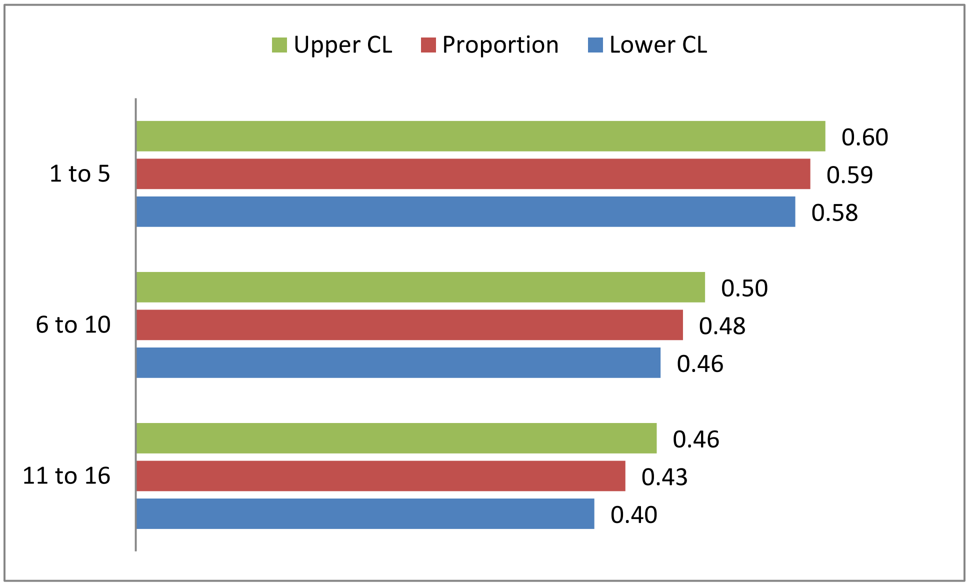


Figure 27. Aggregated Favorable Proportion by Shirt Characteristics for Edited CPW and PMC Studies

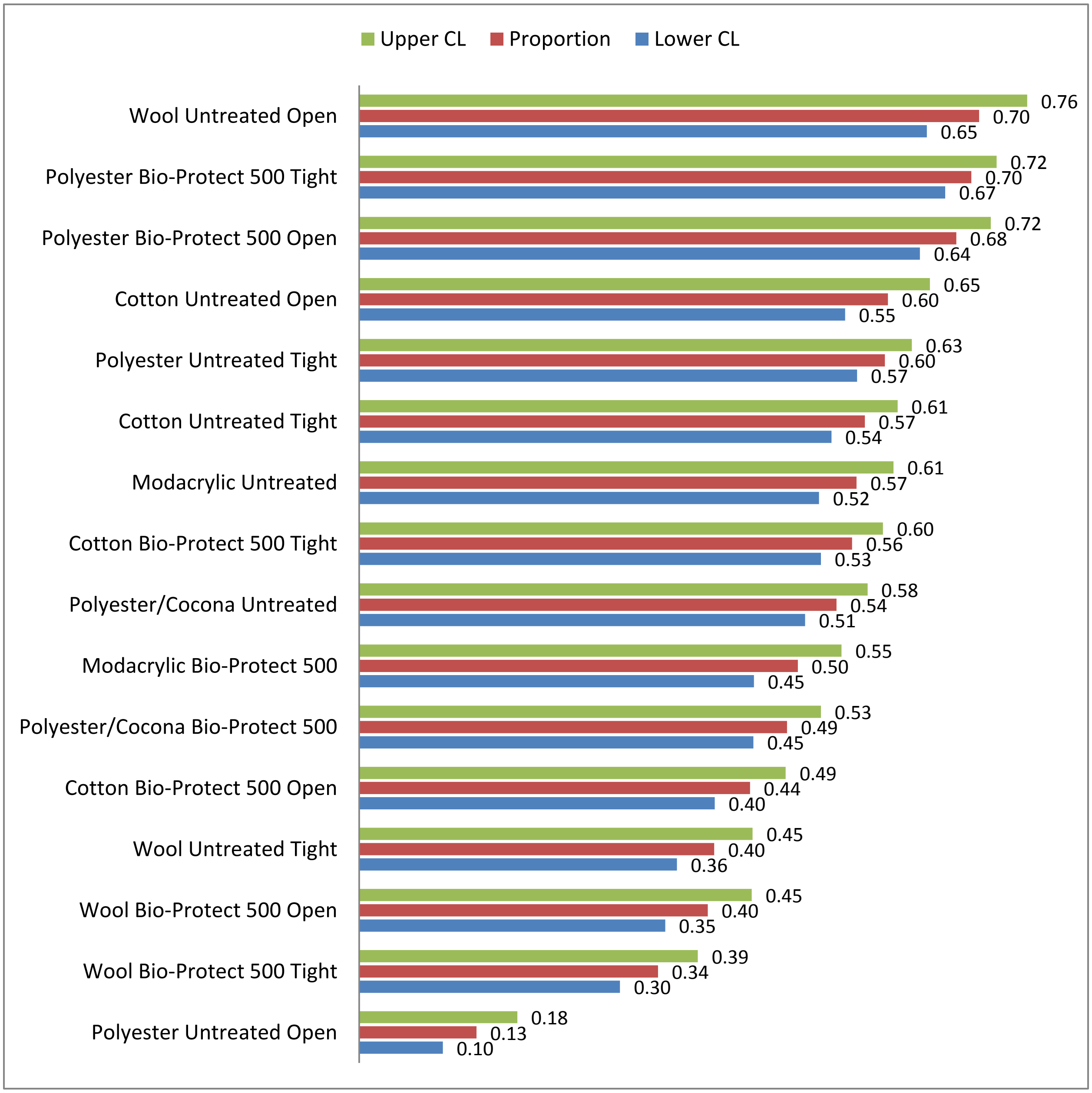


Figure 28. Aggregated Favorable Proportion by Shirt Fabric and Shirt Treatment for Edited CPW and PMC Studies

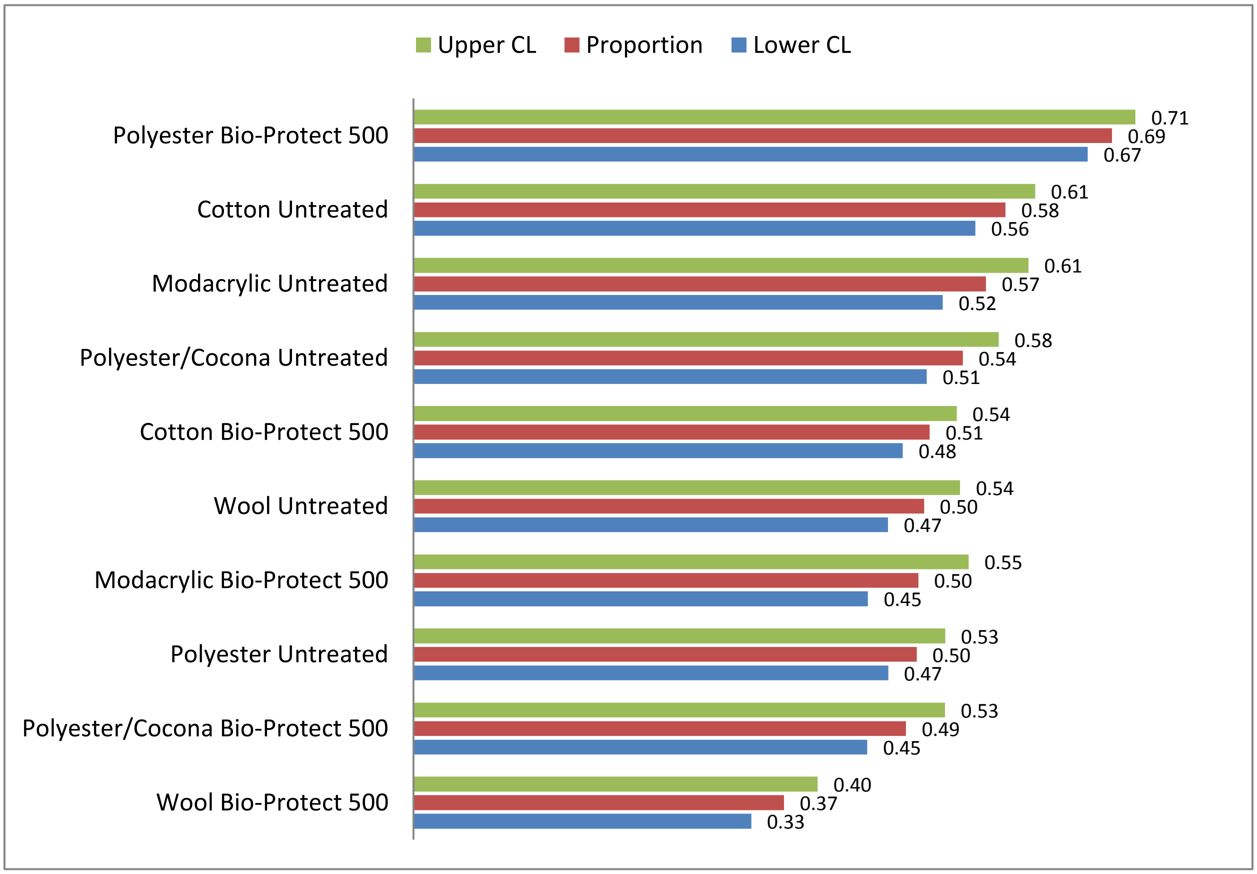


Table 73. Scent Response Prior to New Shirt

New_Scent	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Favorable	11	15.49	11	15.49
Neutral	19	26.76	30	42.25
Unfavorable	41	57.75	71	100.00

Figure 29. Scent Response Prior to New Shirt

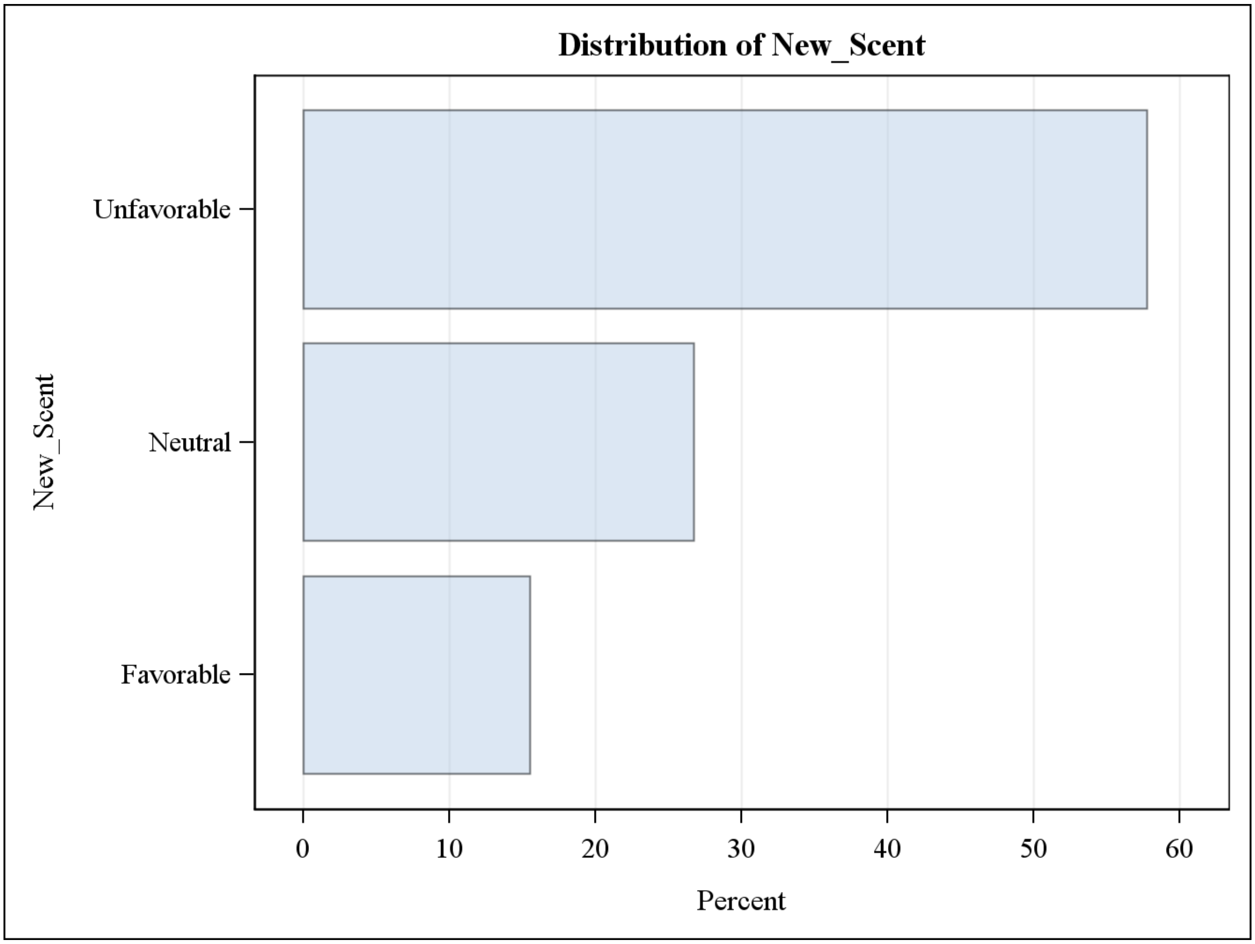
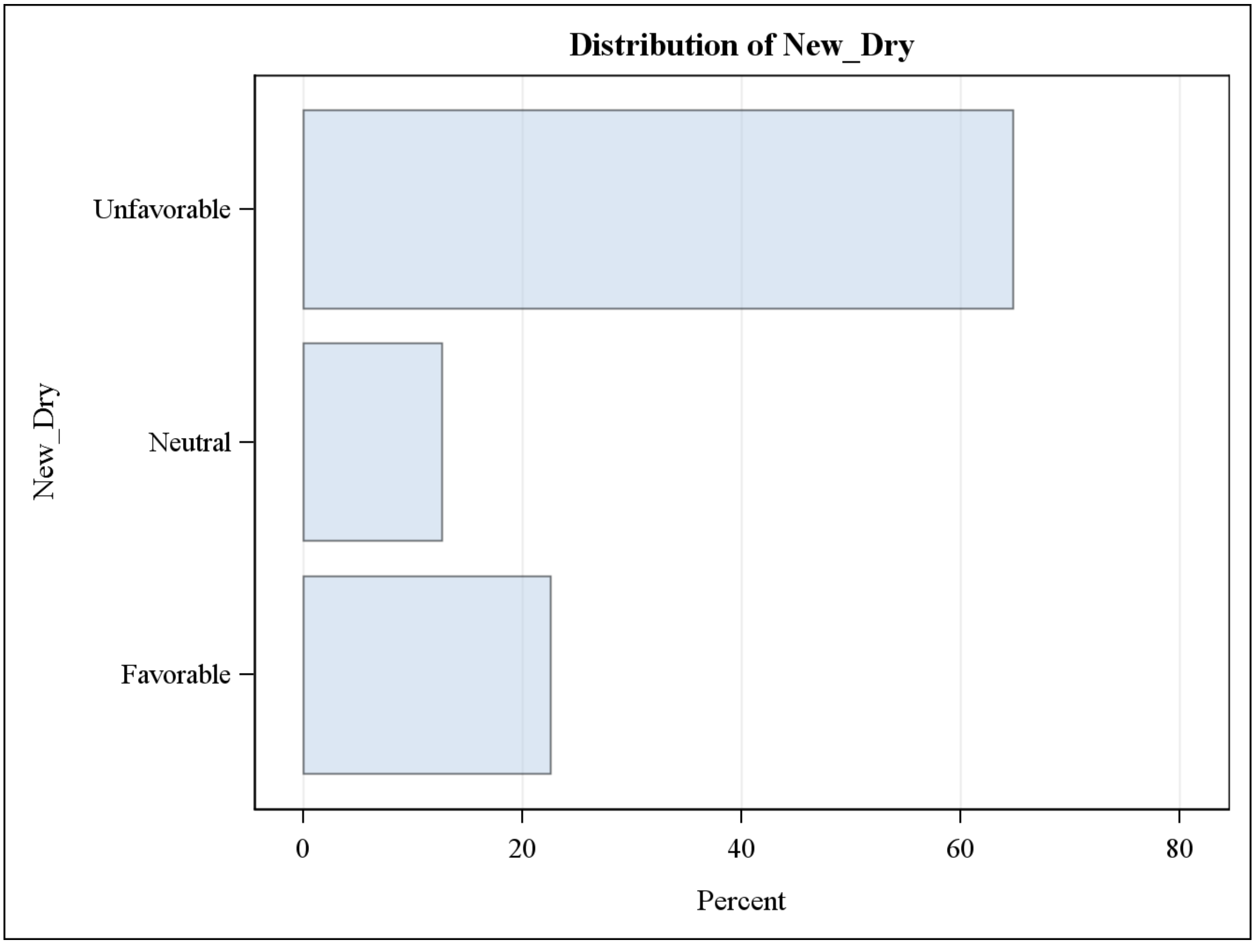


Table 74. Dryness Response Prior to New Shirt				
New_Dry	**Frequency**	**Percent**	**Cumulative Frequency**	**Cumulative Percent**
Favorable	16	22.54	16	22.54
Neutral	9	12.68	25	35.21
Unfavorable	46	64.79	71	100.00

Figure 30. Dryness Response Prior to New Shirt



4.8 Shorts Preferences

For the analysis of shorts preferences, the preference responses for just those shorts that were worn less than 800 minutes were used. This was done to provide comparability with the length-of-wear analysis in Section 4.5.

The proportions of aggregated responses in the categories Favorable, Neutral, and Unfavorable are displayed as bar graphs in Figure 31, Figure 32, Figure 33, and Figure 34 for the levels of the observational variables gender, perceived exertion, days worn and shorts characteristics for the CP shorts study.

For each of the levels of the observational variables gender, perceived exertion, days worn and shirt characteristics, lower and upper 95% confidence levels are displayed in bar graphs for the proportion of aggregated Favorable responses in Figure 35, Figure 36, Figure 37, and Figure 38. It was decided to look with this detail at the aggregated Favorable proportion because the primary technical interest is in the favorable responses. For each level, the proportion is displayed in red in the central bar flanked on each side by a bar for the upper confidence limit in green and the lower confidence limit in blue.

A simple graphical method of determining if two proportions are approximately different statistically is to see if neither proportion lies between the confidence limits of the other proportion. In Figure 35, Aggregated Favorable

Proportion by Gender for Edited CP Shorts Study, the proportion of aggregated favorable responses for male participants is significantly greater than that for female participants. The presence or absence of statistical significance should always be interpreted cautiously. There is a statistically significant difference here for 64% versus 54% which may, or may not, be considered technically significant from the viewpoint of applications.

In Figure 36, Aggregated Favorable Proportion by Perceived Exertion for Edited CP Shorts Study, the proportion of responses in the Light, Hard, and Very Hard levels are significantly different from each other. However, the proportions of responses in the Hard and Very Hard levels differ by only 6%, which may not be technically significant. This result is likely due to a greater tolerance for the condition of the shorts among participants exercising more strenuously.

In Figure 37, Aggregated Favorable Proportion by Days Worn for Edited CP Shorts Study, the aggregated Favorable proportions are the same for shorts used from 6 to 16 days, while the favorable proportion for shorts used from 1 to 5 days is significantly greater, which is to be expected, but only by 7 percentage points.

The aggregated Favorable proportions in Figure 38, Aggregated Favorable Proportion by Shorts Characteristics for Edited CP Study, are arranged from highest to lowest for easier interpretation of the results. The shorts types with the highest aggregated Favorable proportions fall into three groups, from higher to lower proportion:

1. Polyester Woven Untreated
2. Polyester Knitted Untreated, and Cotton Woven Untreated
3. Cotton Knitted Bio-Protect 500

In comparing Figure 38 with the results in Table 70, CP Shorts Fabric by Shorts Construction by Shorts Treatment Least Squares Means, it is seen that the three types of shorts worn the longest, Cotton Woven Bio-Protect 500, Polyester Knitted Bio-Protect 500, and Polyester Woven Bio-Protect 500, are not among the shorts types that have high aggregated Favorable proportions.

The nine preference scales in Table 12 were tabulated to determine the preference responses at the end of the exercise period prior to the period when the old shorts were retired and new shorts were started. The assumption is that an unfavorable assessment of the shorts leads to their retirement. There were two responses that were predominantly unfavorable before new shorts were started, scent and dryness. These responses are evidence of an association between scent and dryness right after exercise and change of shorts in the next exercise period, and not evidence of causality. The tabulations for these responses are displayed in Table 75 and Table 76 and graphically in Figure 39 and Figure 40.

Figure 31. Aggregated Preference Proportions by Gender for Edited CP Shorts Study

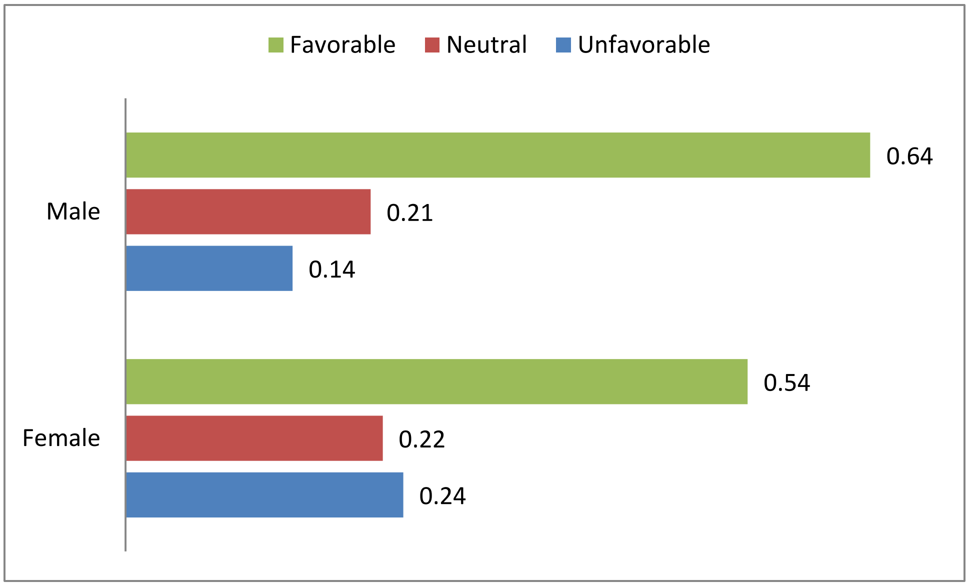


Figure 32. Aggregated Preference Proportions by Perceived Exertion for Edited CP Shorts Study

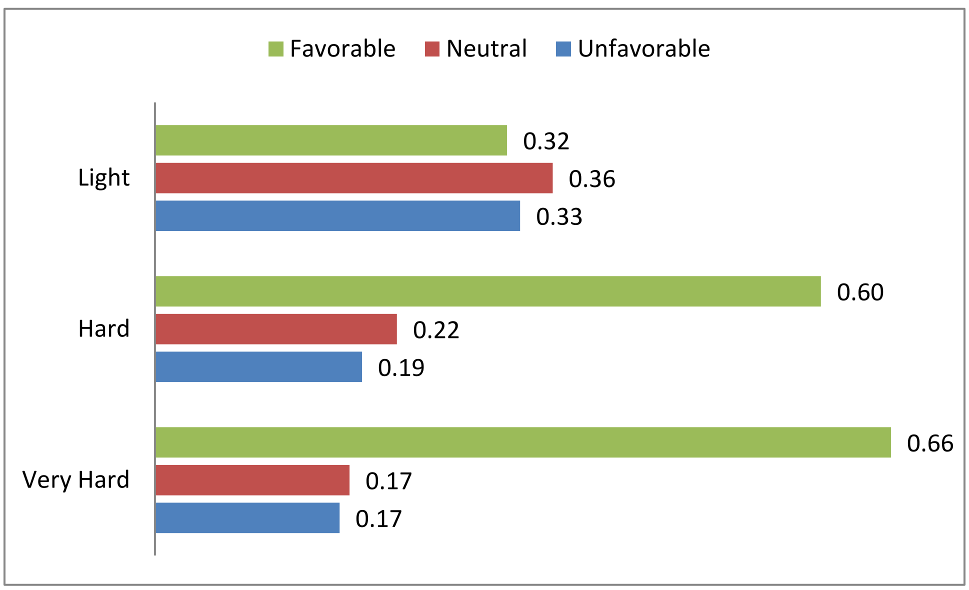


Figure 33. Aggregated Preference Proportions by Days Worn for Edited CP Shorts

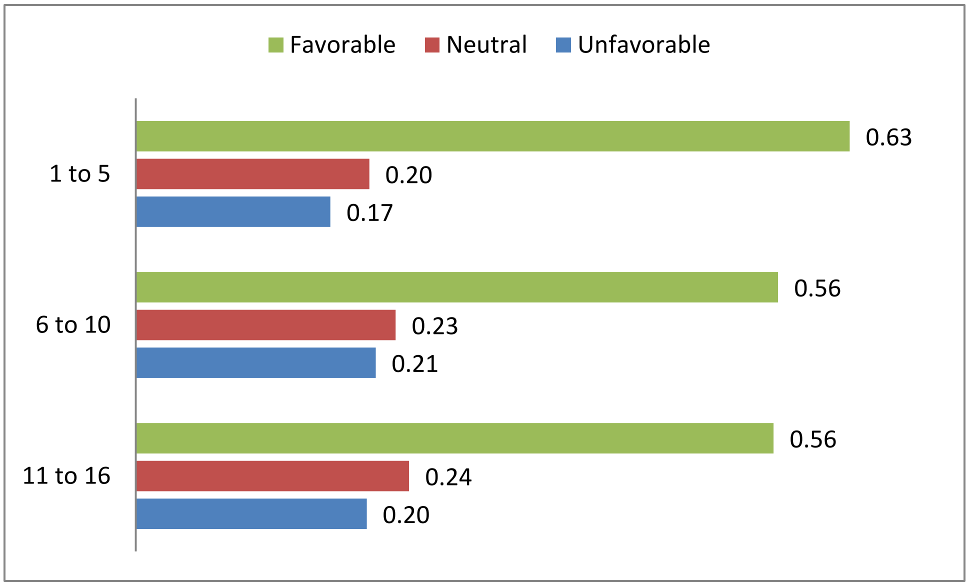


Figure 34. Aggregated Preference Proportions by Shorts Characteristics for Edited CP Study

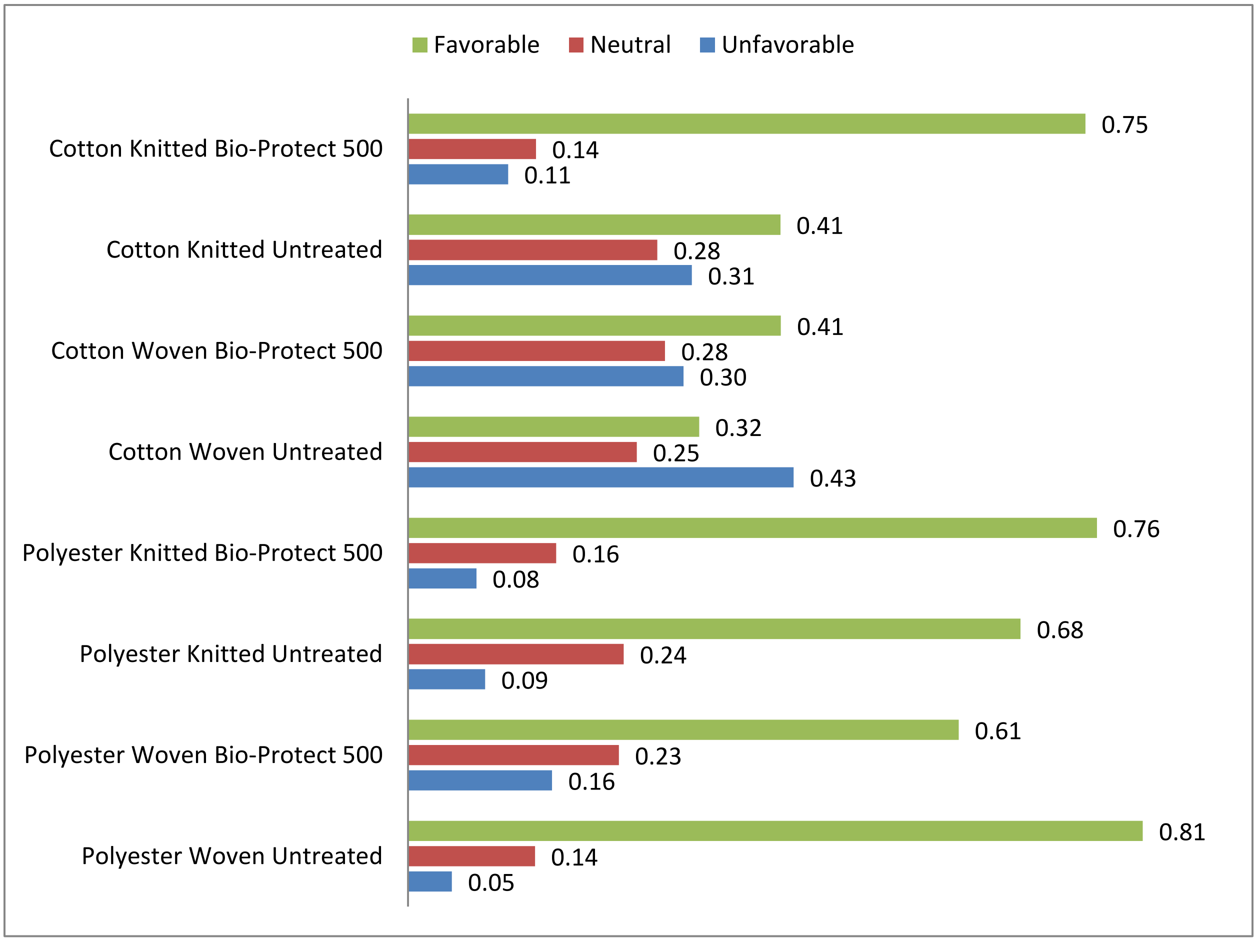


Figure 35. Aggregated Favorable Proportion by Gender for Edited CP Shorts Study

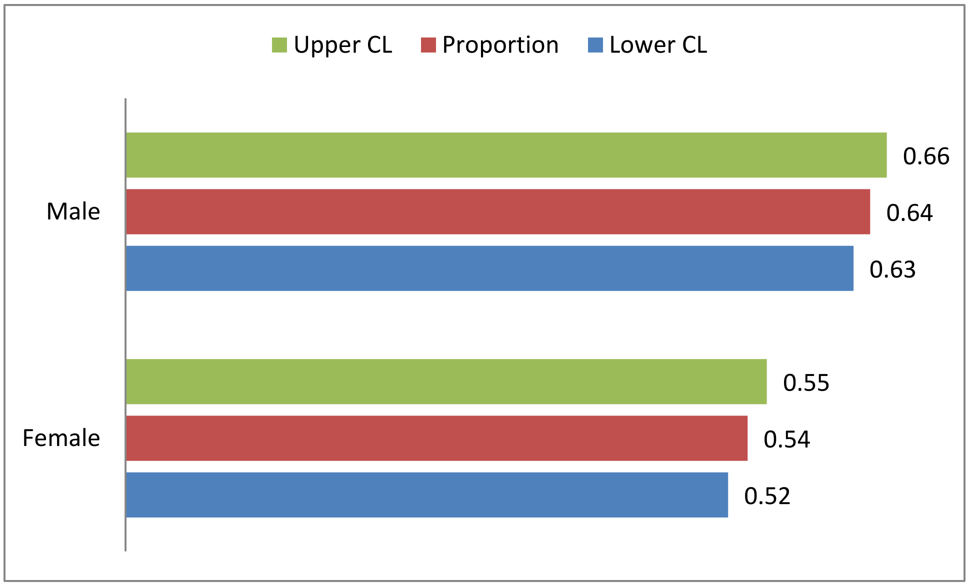


Figure 36. Aggregated Favorable Proportion by Perceived Exertion for Edited CP Shorts Study

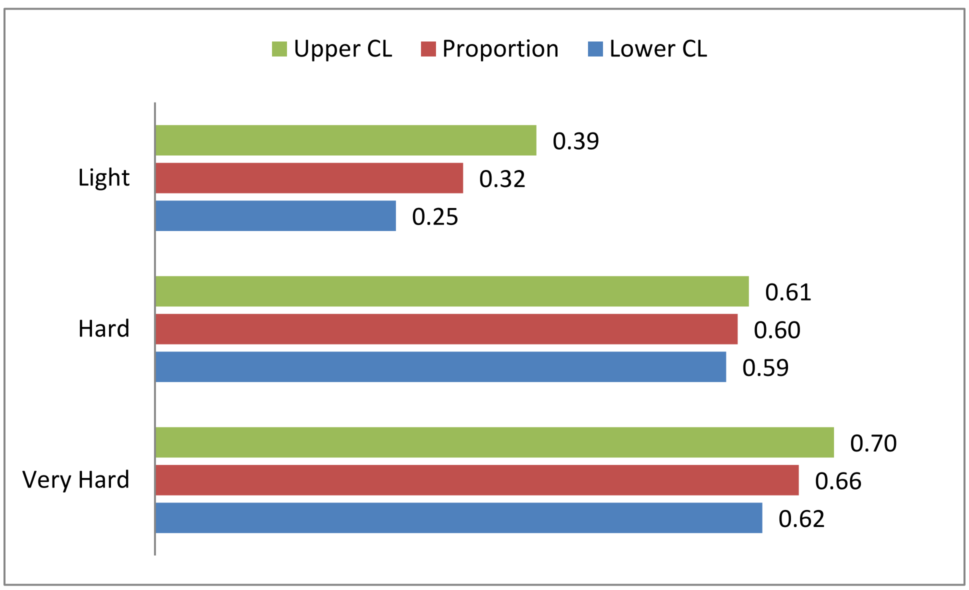


Figure 37. Aggregated Favorable Proportion by Days Worn for Edited CP Shorts Study

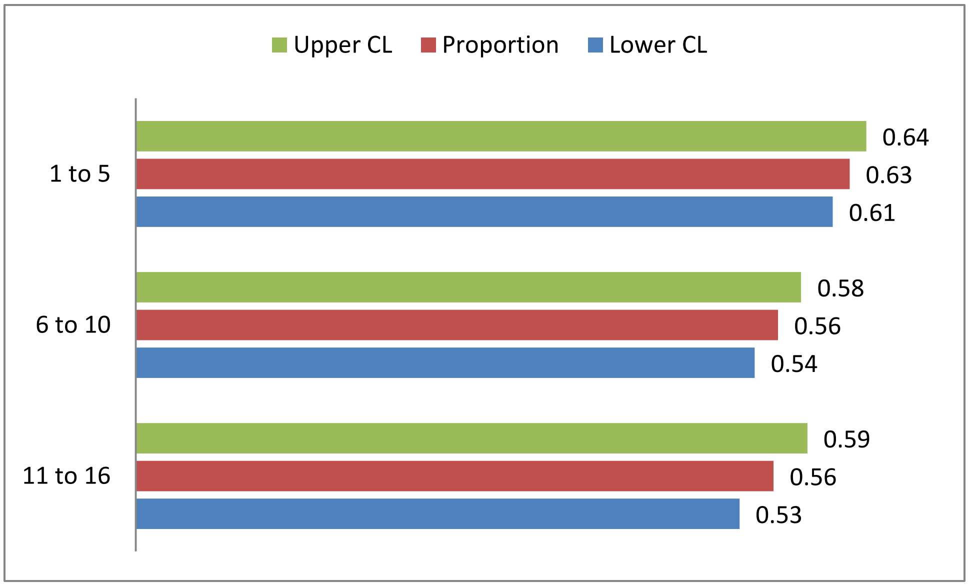


Figure 38. Aggregated Favorable Proportion by Shorts Characteristics for Edited CP Study

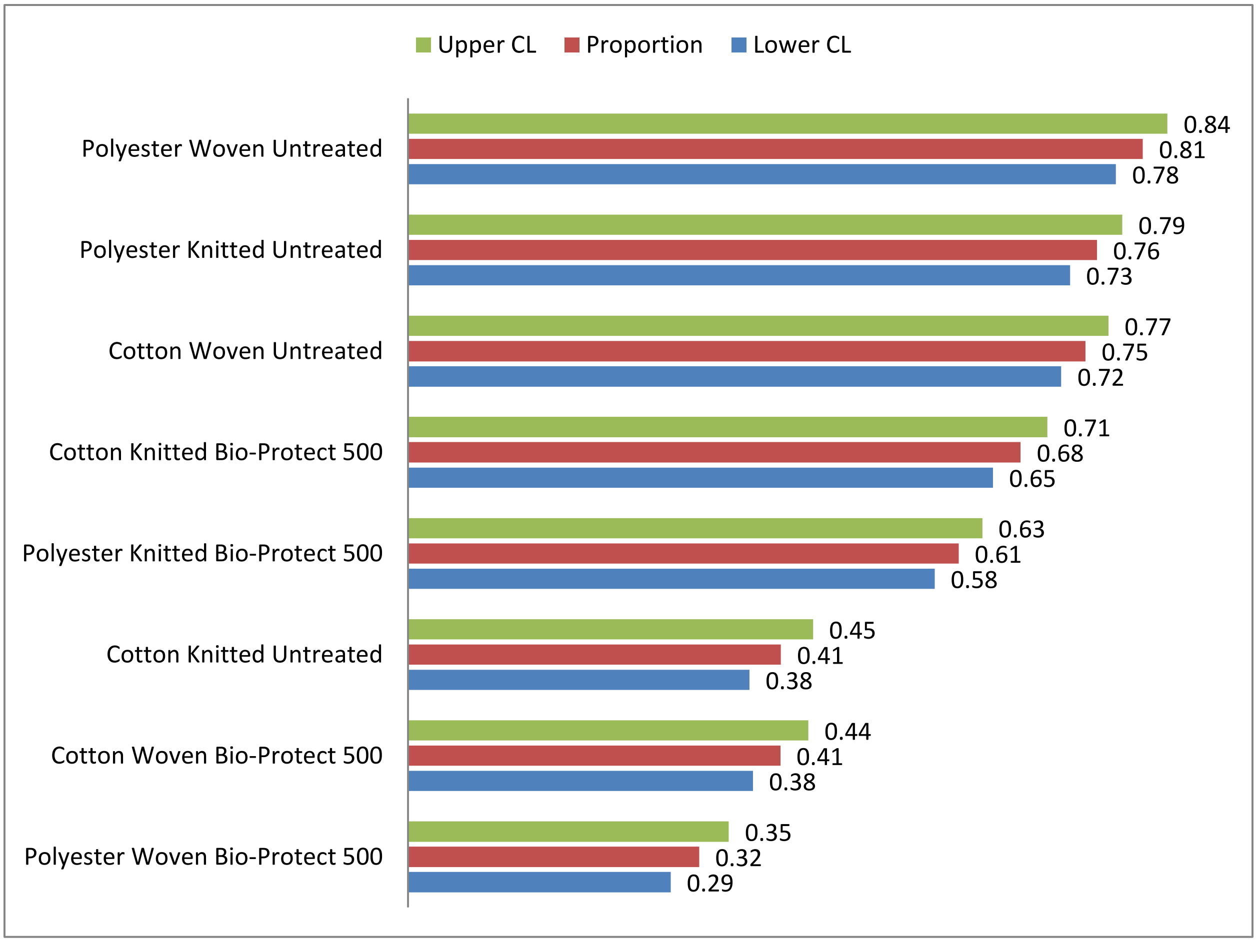


Table 75. Scent Response Prior to New Shorts

New_Scent	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Favorable	13	24.53	13	24.53
Neutral	12	22.64	25	47.17
Unfavorable	28	52.83	53	100.00

Figure 39. Scent Response Prior to New Shorts

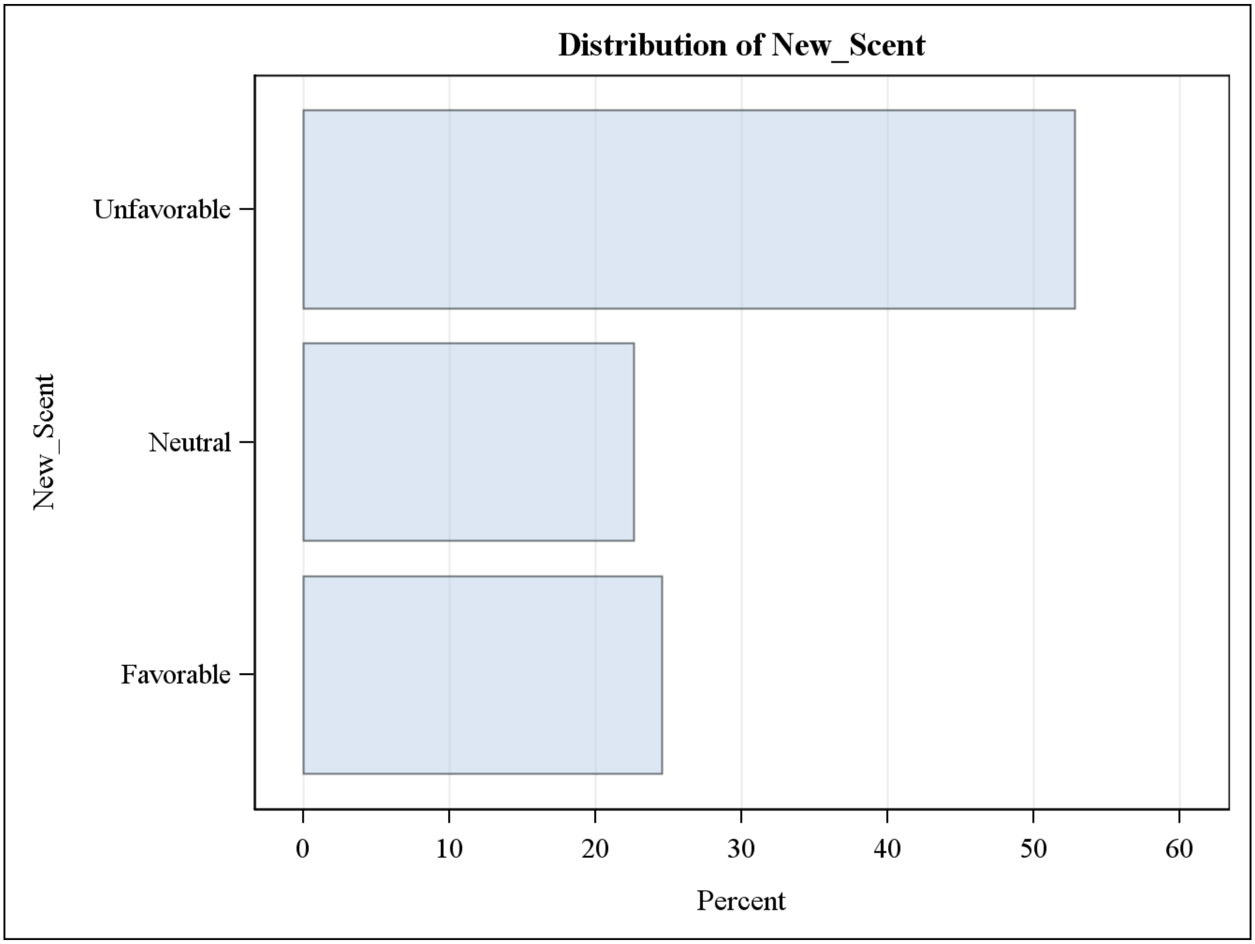
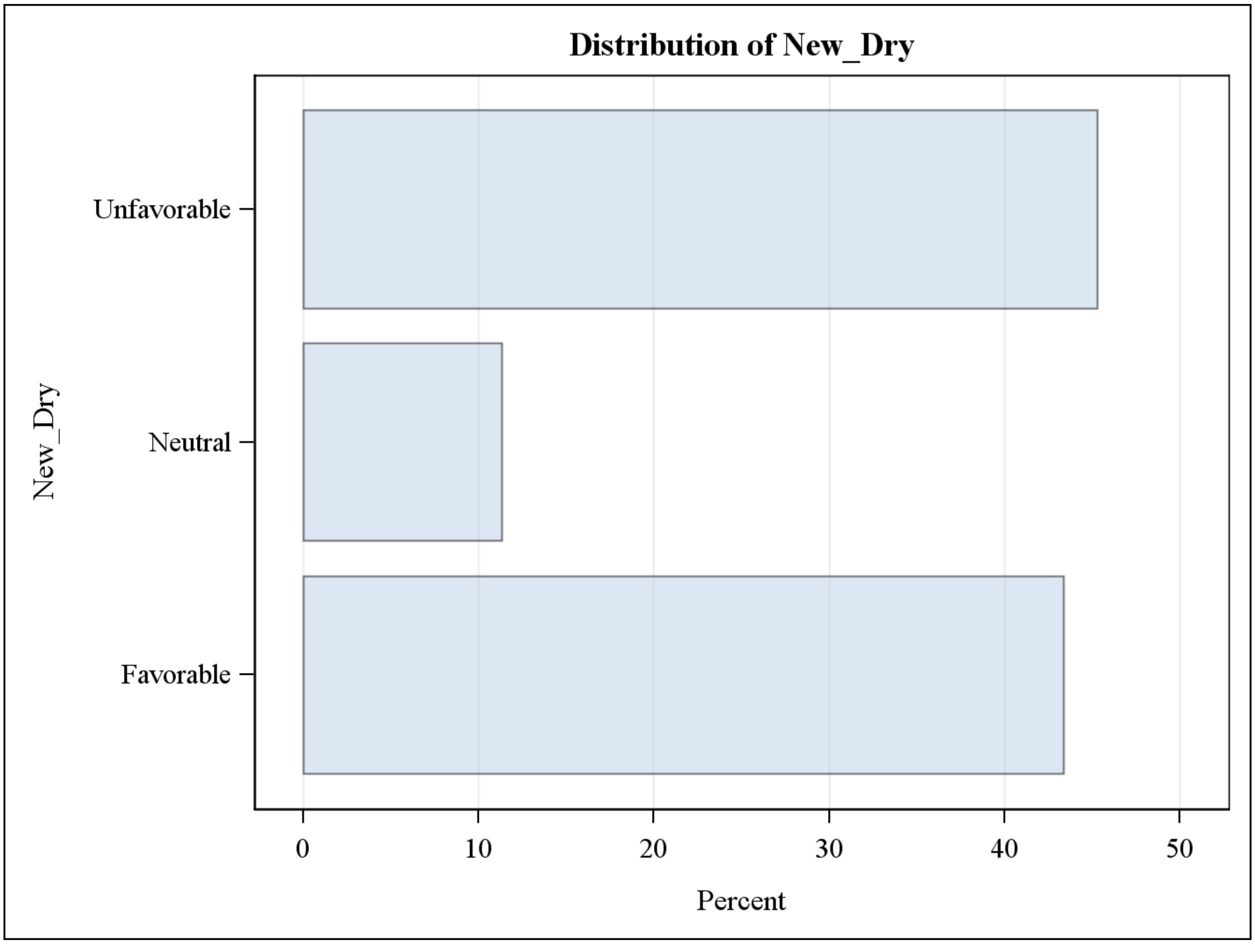


Table 76. Dryness Response Prior to New Shorts

New_Dry	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Favorable	23	43.40	23	43.40
Neutral	6	11.32	29	54.72
Unfavorable	24	45.28	53	100.00

Figure 40. Dryness Response Prior to New Shorts



5.0 CONCLUSIONS

For the combined shirt studies, the exercise shirts with the longest mean lifetimes are untreated wool (600 minutes), treated cotton (526 minutes), and untreated modacrylic (515 minutes). The estimated average minutes of wear for the various treatment combinations of Shirt Fabric by Shirt Treatment are displayed in Table 67, along with lower and upper 95% confidence limits.

The particular treatment combinations with differences in mean lifetimes statistically significant at the 5% level are marked with an asterisk (*) in the right column of Table 68. The additional 199 minutes of mean lifetime for treated cotton compared to untreated cotton is indicative of the adherence and effectiveness of Bio-Protect 500 on cotton. The mean lifetime of untreated wool exceeds that of untreated cotton by 273 minutes. Similarly, the mean lifetime of untreated wool exceeds that of treated modacrylic by 274 minutes. Additionally, the mean lifetime of untreated wool exceeds that of untreated polyester by 240 minutes and that of untreated polyester/cocona, which is 95% polyester, by 237 minutes.

The aggregated Favorable proportions in Figure 27, Aggregated Favorable Proportion by Shirt Characteristics for Edited CPW and PMC Studies, are arranged from highest to lowest for easier interpretation of the results. The shirt types with the highest aggregated Favorable proportions fall into three groups, from higher to lower proportion:

1. Wool Untreated Open-Knit, Polyester Bio-Protect 500 Tight-Knit, and Polyester Bio-Protect 500 Open-Knit
2. Cotton Untreated Open-Knit, Polyester Untreated Tight-Knit, Cotton Untreated Tight-Knit, and Modacrylic Untreated (Tight-Knit)
3. Cotton Bio-Protect 500 Tight-Knit, and Polyester/Cocona Untreated (Tight-Knit)

In comparing Figure 27 with the results in Table 67, Combined CPW and PMC Shirt Fabric by Shirt Treatment Least Squares Means, it is seen that the most preferred material, Wool Untreated Open-Knit, contributes to the material that was worn the longest, Wool Untreated. For comparability to the length-of-wear analysis, Figure 28 displays the favorable proportion of aggregated responses for which the data for the two types of knit, open and tight, have been combined under their respective combinations of fabric and treatment. The much lower favorability of untreated wool in Figure 28 is due to the adverse favorability seen in Figure 27 for treated wool and untreated tight-knit wool.

The nine preference scales in Table 12 were tabulated to determine the preference responses at the end of the exercise period prior to the period when the old shirt was retired and a new shirt was started. The assumption is that an unfavorable assessment of the shirt leads to its retirement. There were two responses that were predominantly unfavorable before a new shirt was started, scent and dryness. These responses are evidence of an association between scent and dryness right after exercise and change of shirt in the next exercise period, and not evidence of causality. The tabulations for these responses are displayed in Table 73 and Table 74 and graphically in Figure 29 and Figure 30.

For the CP shorts study, there were no statistically significant differences in mean lifetimes of the exercise shorts at the 5% significance level due to the treatment combinations. There was therefore no justification to examine differences among levels of main effects or interactions. For reference, the estimated average minutes of wear for the various treatment combinations of CP Shorts Fabric by Shorts Construction by Shorts Treatment are displayed in Table 70, along with lower and upper 95% confidence limits.

The aggregated Favorable proportions in Figure 38, Aggregated Favorable Proportion by Shorts Characteristics for Edited CP Study, are arranged from highest to lowest for easier interpretation of the results. The shorts types with the highest aggregated Favorable proportions fall into three groups, from higher to lower proportion:

1. Polyester Woven Untreated
2. Polyester Knitted Untreated, and Cotton Woven Untreated
3. Cotton Knitted Bio-Protect 500

In comparing Figure 38 with the results in Table 70, CP Shorts Fabric by Shorts Construction by Shorts Treatment Least Squares Means, it is seen that the three types of shorts worn the longest, Cotton Woven Bio-Protect 500, Polyester Knitted Bio-Protect 500, and Polyester Woven Bio-Protect 500, are not among the shorts types that have high aggregated Favorable proportions.

The nine preference scales in Table 12 were tabulated to determine the preference responses at the end of the exercise period prior to the period when the old shorts were retired and new shorts were started. The assumption is that an unfavorable assessment of the shorts leads to their retirement. There were two responses that were predominantly unfavorable before new shorts were started, scent and dryness. These responses are evidence of an association between scent and dryness right after exercise and change of shorts in the next exercise period, and not evidence of causality. The tabulations for these responses are displayed in Table 75 and Table 76 and graphically in Figure 39 and Figure 40.

6.0 RECOMMENDATIONS FOR FUTURE WORK

The LRR project was approved for a 3 year period, FY12-FY14, but may be extended past FY14. The last planned activities for the ACS task are the completion of the ISS technology demonstration, the establishment of the collaborative effort with the ISS Mission Integration and Operations Office, and a few other clothing studies in the Crew and Thermal Systems Division at JSC. These studies will be designed to address findings from the previous studies. For example, it is desirable to better understand the effectiveness of antimicrobial treatments on fabrics. It is also important to study wool for other uses in crew clothing and in their quarters.

7.0 ACKNOWLEDGEMENTS

The project team members for the ground study included Vicky Byrne, Brenda Cooper, Sarah Luna, Evelyne Orndoff, Dina Poncia, Darwin Poritz, and Thilini Schlesinger.