ABSTRACT

FRATTO, LISA A. Evaluating the Performance of Fibers and Fabrics for Astronaut's IVA Wardrobes for Long Duration Space Flight. (Under the direction of Dr. Roger Barker and Dr. Nancy Cassill.)

Intravehicular clothing has not been recognized by NASA as a critical element of space exploration up until this point. The NASA Standard 3000 for Crew Personal Equipment includes an explanation of clothing guidelines, but lacks rigid requirements or measurable performance levels for IVA clothing. With the advent of a long duration mission to Mars, NASA is seeking innovative ways to reduce the weight impact and linting problems associated with IVA clothing during long duration space flight. This research provides NASA with recommendations for improved IVA apparel and a framework for the appropriate selection of IVA clothing materials based on objectively measurable material properties and performance needs for IVA use.

There are many differences between working in a weightless environment in space and working in the gravity of Earth's environment that should be addressed in clothing selection. A thorough examination of clothing and mission needs for long duration space flight was conducted in order to propose the best candidates based on scientific analysis. Requirements for current and historical programs were documented, with particular focus on long duration and ISS missions. NASA standards, NASA documents related to clothing, and related commercial standards (NFPA, ASTM) were reviewed.

Based on this analysis, a list of requirements to be applied to clothing for long duration space flight was developed. These include: lightweight, low volume, low linting, safe, comfortable, durable, easy to care for, and acceptable appearance.

After determining the requirements, material properties associated with each of these performance requirements were identified. Garment materials that met these requirements were then identified and tested. These tests will verify critical performance characteristics. The fabric and fiber candidates chosen were compared against these criteria. The results from this research provide NASA with a list of recommended fibers/fabrics for IVA use as well as an appropriate method they can use to select wardrobe materials for IVA use.

EVALUATING THE PERFORMANCE OF FIBERS AND FABRICS FOR ASTRONAUT'S IVA WARDROBES FOR LONG DURATION SPACE FLIGHT

by

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BIOGRAPHY

The author, Lisa A. Fratto, was born in Melrose, Massachusetts on August 7, 1980. Her parents are Robert and Donna Fratto and she has an older sister named Genessa and a twin sister named Cara. Lisa grew up in Sandwich, Massachusetts and moved to Cary, North Carolina in the summer of 1993. She graduated from Cary High School in 1998 and went on to study business at the Kenan-Flagler Business School at The University of North Carolina at Chapel Hill. She graduated with a Bachelor of Science in Business Administration with a concentration in Marketing in May of 2002. After graduating, she obtained a position as an Executive Trainee with Belk, Inc. where she learned about many aspects of the retail and apparel business. After working as an Area Sales Manager for Belk in Sanford, North Carolina, she decided to pursue her Master of Science Degree in Textile and Apparel Technology and Management. She is currently completing the requirements for her graduate degree and looks forward to a career in the apparel industry.

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CHAPTER I

INTRODUCTION

The definition of living in space has changed dramatically since the earliest human spaceflight missions. During the Mercury Program in the 1960s, the first six astronauts in space accumulated less than 54 collective mission hours. The longest Apollo mission (Apollo 17) lasted 12 days. The longest Space Shuttle mission (STS-80, 1996) lasted 17 days. The Skylab's longest residential duration was 84 days and the Expedition 7 crew lived on the Space Station for six months ("JSC NASA Facts," 2004). Plans for travel to Mars will move human spaceflight duration from days and months into years.

The advent of the Mars program, and the goal of manned Mars missions by the year 2030, has spawned a review of the materials and processes currently used for long duration space flight (LDSF). Special emphasis is placed on incorporating new technologies within the life support system that will have a dramatic impact on the reduction of mass and waste and provide increased safety and reliability for LDSF (The Boeing Company, 2002).

Intravehicular activity (IVA) clothing, worn by astronauts inside the spacecraft during travel and on-orbit activities, is made up largely of cotton which contributes significantly to the weight and waste impact on the shuttle. An improvement in the performance of IVA clothing would help to reduce these impacts. Since human spaceflight began, there have been many textile developments for targeted applications, such as athletic apparel and protective clothing, which possess high performance properties that may be used for space clothing applications.

IVA clothing supply has a significant impact on mission mass and total waste mass for LDSF. The adoption of washable, lightweight clothing that is reused throughout the mission would reduce the system mass on the shuttle and eliminate the necessity to replenish materials. Lint is also a problem in the weightless space environment. Lint fibers are dislodged from the cotton garments, towels and other fabrics used in space, causing filters to become clogged and interfering with operations. Appropriate IVA clothing for a long duration mission to Mars should reduce waste and weight while still maintaining functionality, durability, protection, comfort, and aesthetics (The Boeing Company, 2002).

The current IVA wardrobe consists of sweaters, jackets, t-shirts, pants, undergarments, socks, and athletic shorts. Astronauts select and order in advance all garments for a mission wardrobe from the official NASA Joint Crew Provisioning Catalog (JCPC). All main clothing garments are a selection of commercial off-the-shelf (COTS) items and are at least 95% cotton (A. Whitaker, personal communication, January 2004). Intravehicular clothing typically requires only minimal protection from the intravehicular environment. Therefore, the standards that exist for IVA crew clothing are vague. The NASA Standard 3000 for Crew Personal Equipment includes an explanation of IVA clothing guidelines, but lacks rigid requirements or measurable performance levels.

There are many differences between working in a weightless environment in space and working in the gravity of Earth's environment that should be addressed in clothing selection. A thorough examination of clothing and mission needs for long duration space flight is necessary in order to propose the best candidates based on scientific analysis. Requirements for current and historical programs, with particular focus on long duration and International Space Station (ISS) missions, NASA standards, NASA documents related to clothing, and related commercial standards were reviewed. Based on the analysis, a list of requirements to be applied to clothing for long duration space flight was developed. Through this research, these issues were analyzed and ranked to determine their importance in the development of appropriate IVA clothing for long duration space travel.

After determining the requirements, material properties associated with each of these performance requirements were identified. The best candidate garment materials that met these requirements were then identified and tested to verify critical performance characteristics. The candidates chosen were compared against the criteria of a proposed standard and the NASA Standard 3000. The results from this research provide NASA with a list of recommended materials for IVA clothing use as well as an appropriate method they can use to select wardrobe materials for future use in long duration space travel.

Susan Watkins' recommended design process for functional apparel provides the conceptual framework for this study. Though the IVA apparel will not be designed, but rather chosen from COTS garments, her framework is still applicable to this functional apparel design problem. Her step-by-step method includes analysis, definition, ideation, idea selection, and evaluation. According to Watkins, "These are the critical steps which cannot be ignored in the development of effective functional clothing" (Watkins, 1995, p. 336).

There has been little research done on IVA clothing and how using different garment materials can affect mission variables. Research is needed to determine if the adoption of new IVA garments can significantly affect the impacts of weight and waste while maintaining comfort and increasing safety and reliability.

Purpose of this Study

The purpose of this study is to evaluate and recommend materials for use in astronaut's IVA wardrobes based on the needs and requirements of LDSF, and to develop a model that would allow NASA to systematically select appropriate clothing for IVA clothing applications. The objectives of this study are as follows:

1. Collect information on astronaut and environmental needs as well as NASA and related standards and practices.
2. Define the performance requirements for IVA clothing.
3. Perform a market survey of COTS materials that could potentially meet requirements and represent the latest in textile innovation.
4. Select candidate garments whose performance claims best match IVA requirements.
5. Identify the test methods best suited to measure the critical performance categories of each garment.
6. Test candidate materials according to standardized test procedures in order to verify performance characteristics.
7. Evaluate the performance of each garment compared to others and recommend the candidate garments that best meet requirements and rate highest on performance and user priorities for IVA use.
8. Use the above results and processes to develop a model for NASA to guide in future selection of IVA clothing.

Significance of this Study

There is limited documented research on IVA clothing and no documented research on long duration clothing for manned missions to Mars. This study provides documentation for redefining clothing standards for long duration space flight (LDSF) through the evaluation of innovative new textile products. A modification of the materials used for IVA travel can greatly reduce the critical impacts of weight and waste and therefore affect the success of a long duration mission. The model developed in this study will allow NASA to select IVA clothing for LDSF in a more systematic manner.

Limitations of this Study

The limitations of this study relate to market availability, the scope of the garment selection, the testing environment, and the collection of primary user data.

Market Availability

According to the NASA Standard 3000, NASA prefers using COTS garments rather than developing custom-made garments. Therefore, the study is limited to products readily available on the market. Also, while textile innovations are available in abundance today, there is no way of knowing what will be available 20 years from now when manned Mars missions actually begin.

Garment Selection

Time constraints have limited the wardrobe items chosen for testing. While the current IVA wardrobe consists of sweaters, jackets, t-shirts, pants, undergarments, socks, and athletic shorts, the IVA t-shirt was chosen as a representative focus garment for this study. Therefore, efforts to find garments in the targeted COTS materials focused only on those textile innovations available in a t-shirt form. Due to time constraints, only ten garments were chosen for testing which is limited when compared to the universe of textile innovations in clothing that could have been tested.

In addition, the material properties of each shirt, such as type of knit, yarns, and treatments, will most likely not be equivalent for head-to-head comparisons as would be desirable for research purposes.

The Testing Environment

While the tests chosen for evaluation were conducted according to standard procedures, there is no practical way to take into account the effects of a zero or micro-gravity environment. Garment properties could possibly perform differently in this environment.

Primary User Data

Contact was made with the astronaut office at NASA, which allowed access to a former astronaut for questioning and guidance. However, interviewing a group of astronauts was not allowed, and therefore, this study relied mainly on secondary data to determine the needs of the astronauts.

Acronyms

ASTM	=	American Society for Testing and Materials
COTS	=	Commercial Off-the-Shelf
EVA	=	Extravehicular Activity
ISS	=	International Space Station
IVA	=	Intravehicular Activity
JCPC	=	Joint Crew Provisioning Catalog
JSC	=	Johnson Space Center
LDSF	=	Long Duration Space Flight
NASA	=	National Aeronautics and Space Administration
NFPA	=	National Fire Protection Association
STS	=	Space Transportation System

Definition of Terms

Commercial off-the-shelf (COTS) - Items that are manufactured commercially and are readily available to all consumers in the marketplace. IVA clothing is a selection of COTS garments as opposed to garments that are custom made.

Extravehicular activity (EVA) - Any activity taking place outside the spacecraft.

Extravehicular activity clothing - Clothing worn outside the spacecraft that is required to comply with rigid requirements in order to protect the wearer from the hostile space environment.

Intravehicular activity (IVA) - Any activity taking place inside the spacecraft.

Intravehicular activity clothing - Clothing that is worn by astronauts inside the spacecraft during on-orbit activities. The IVA wardrobe consists of sweaters, jackets, t-shirts, pants, undergarments, socks, and athletic shorts. IVA clothing is not required to comply with the rigid protection requirements of pressurized clothing or EVA clothing, and therefore is similar to normal clothes that provide functionality and comfort in performance.

Joint Crew Provisioning Catalog (JCPC) - A document that provides crew members with pictures and descriptions of the available selection of flight crew equipment. All items listed in the catalog have been certified and approved for use. ISS and space shuttle crewmembers select wardrobe items from the JCPC months before they are scheduled to launch. The catalog consists mainly of 100% cotton knit clothing.

Long duration space flight (LDSF) - Any spaceflight mission lasting 14 days or more has been referred to as long duration in the NASA literature reviewed for this paper. A Mars mission will be the longest duration space flight, lasting up to three years.

NASA Standard 3000 - A NASA document created to provide a single, comprehensive document defining all generic requirements for space facilities and related equipment which directly interface with crewmembers (National Aeronautics and Space Administration, 2004).

CHAPTER II

LITERATURE REVIEW

A look at the unique needs of astronauts and the space environment as well as the possibilities emerging as a result of technological advances in textiles and apparel provides an overview of the issues that must be considered before an improved IVA wardrobe can be selected. The development process for functional apparel serves as an appropriate framework for choosing apparel products that support those with special needs.

Functional Apparel

"Clothing is our most intimate environment…it is carried everywhere with an individual, creating its own room within a room and its own climate within the larger climate of our surroundings" (Watkins, 1995, xv). The control and maintenance of this environment can be accomplished through the use of functional apparel.

Functional apparel can provide shelter or protection for the human body, help accommodate disabilities, increase health and safety, improve efficiency, and increase body function (Watkins, 1995). It is often created for a particular group of users with similar needs. These needs arise due to interactions with the environment. Examples of functional apparel include rainwear, thermal underwear, foundation garments, and exercise attire (Lamb & Kallal, 1992).

All apparel items must meet minimal functional and aesthetic requirements (May-Plumlee, 2002). This idea is represented through May-Plumlee's Aesthetic-Functional continuum shown in Figure 1. A garment's location on the continuum is determined by the balance of functional and aesthetic requirements. Surgical gowns are dominated by performance needs and therefore located near the functional end (May-Plumlee, 2002).

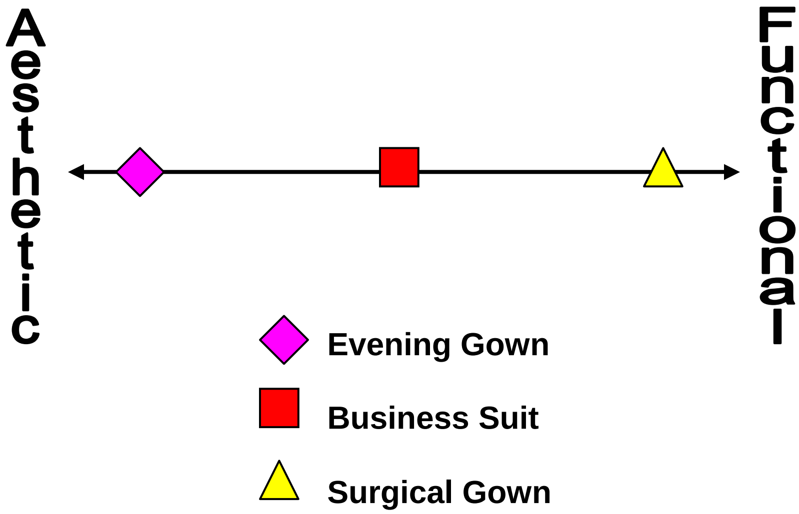

Figure 1: Aesthetic-Functional Continuum

Source: May-Plumlee,Traci and Pittman, Amanda. (2002). Surgical Gown Requirements Capture: A Design Analysis Case Study. *Journal of Textile and Apparel Technology and Management, 2,* 1-10.

The level of functionality required for apparel depends on the situation of the user. According to Rosenblad-Wallin (1985), use-situations create special functional demands for garments. Demands arising from the use-situation are determined from descriptions and evaluations of relevant factors in the use-situation including activities and environments (Rosenblad-Wallin, 1985).

Functional Apparel Design Processes

Though IVA apparel will not be specially designed, but rather chosen from COTS garments, the design process for functional apparel provides a useful model for the selection of apparel for astronauts and is applicable to this problem solving research. Susan Watkins recommends six critical steps in the design process. These steps provide the conceptual framework for this study. Rosenblad-Wallin, also a pioneer in functional design, presents a model similar to Watkins.

Watkins's Process

Though very little has been written about product development processes specifically for apparel, Susan M. Watkins has written extensively on the design process for functional apparel. In the Second Edition of her book, *Clothing: The Portable Environment*, Watkins outlines a typical new product development process for functional apparel. This process, shown in Figure 2, has been used in some form by many developers of functional apparel.

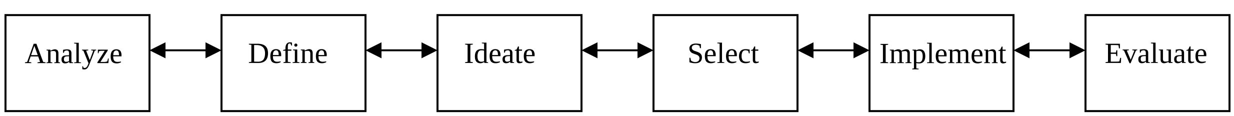

Figure 2. Typical Development Process for Functional Apparel

Source: Watkins, Susan M. (1995). *Clothing: The Portable Environment* (2^{nd} ed.).
Ames, IA: Iowa State University Press.

According to Watkins, analysis of the design process should occupy the vast majority of the product development effort. A thorough analysis assures subsequent stages will be more productive. Analysis includes basic exploratory research that helps designers become familiar with the problem and the products users. Data collecting methods in the analysis phase include direct observation, participant observation, indirect observation, direct communication, questionnaires, or laboratory simulation. A literature review of existing research in the area as well as learning the language of the field and interviewing specialists in the field are crucial first steps. According to Watkins, "It is imperative that the designer understand hazards in the environment and the various needs of the wearers" (Watkins, 1995, p. 339). These methods help the designer to analyze the design problem. Watkins even advises using all methods if possible to overcome the weaknesses inherent in each method. For analysis, Watkins also suggests exploring databanks of organizations that might be concerned with functional apparel such as government agencies and standards groups like the American Society for Testing and Materials (ASTM) or the National Fire Protection Association (NFPA).

A thorough analysis helps set a clearer definition of the true wearer needs on which the design solutions could be based. Definition, the second step in the process, is a statement of the goals a designer needs to meet to solve a problem. The information collected in the analysis phase is sorted through and the most essential elements are determined. Watkins emphasizes the importance of completing a thorough analysis before attempting to define a problem. This prevents designers from working to solve the wrong problem. A proper definition forms the basis for determining if a particular product satisfies the needs of the user. Watkins claims that in functional design research, "the bulk of the data collection is aimed at setting goals—at defining the true problem" (Watkins, 1995, p. 341). The definition forms the basis for evaluation of design ideas.

Ideation is the creative part of the NPD process for functional apparel. Watkins emphasizes the fact that a majority of ideas generated for functional or protective apparel do not come in a flash of genius. They are usually the result of hours, weeks, or even years of disciplined preparation and analysis. There are many methods used by functional designers to generate new ideas and design concepts. Some commonly used techniques include brainstorming, synetics, and mind mapping (Watkins, 1995).

Idea selection involves selecting the design ideas that best solve a problem. Designs must be broken down into smaller concepts, or attributes, and then explored and evaluated individually. It is important in this phase to prioritize criteria so that the importance of each plays an appropriate role in the selection of the final design. A matrix is commonly used to select design features for functional apparel. The matrix includes features of the apparel product which are weighted and scored based on their potential to meet design criteria. An interaction matrix is another important tool. The matrix identifies the criteria that are likely to be in conflict with one another. In Watkins' (1995) words, "When the best solution to one criterion exacerbates the problem expressed by another, the designer has to determine the relative importance of each criterion and work to develop a design solution that maximizes the benefits for both" (p. 351).

Implementation is the point where the product evolves from the process and the chosen ideas are put to work. Evaluation is a time for assessment before moving ahead. It may involve numerical ratings based on tests or the informal subjective opinion of the designer. Product and standards testing occurs in this phase and final garments are evaluated (Watkins, 1995).

Rosenblad-Wallin's Process

Rosenblad-Wallin (1985) presents a user-oriented functional apparel development process, meaning the focus is on the user and the use-situation. The nine step method includes:

1. Identification of the problem area
2. Problem analysis
3. Formulation of objective and project
4. Formulation of the demands of the user, the use-situation and general demands based on user studies, interviews, environmental mappings, measurements and other investigations
5. Data processing and analysis
6. Specification of the use-demands and transformation of these into technical terms
7. Development of ideas and technical solution
8. Evaluation, modification and selection of prototype
9. Evaluation of the final solution in relation to the objectives

This process is similar to Watkins's process. In both processes, user needs or demands are specified and transformed into measurable technical terms and evaluated on their effectiveness in meeting the most pressing needs based on apparel objectives.

History of Clothing in Space

The first manned space flights were short in duration, lasting less than a day. Clothing was designed to provide protection from the hostile space environment. During the Mercury program (1958-1963), Al Shepard and the five Mercury pilots wore adaptations of a U.S. Navy pressure suit. The Mercury suit was worn unpressurized and served as a backup for possible spacecraft cabin pressure loss, an event which never actually occurred. It was difficult for the astronauts to bend their arms and legs in a pressurized suit ("JSC NASA Facts," 1984).

The pressurized spacesuit worn by the Gemini crew (1965-1966) provided greater mobility. An inner layer was added to the suit which reduced stiffness and made the suit more comfortable when worn unpressurized for the longer duration Gemini flights, which lasted up to fourteen days ("JSC NASA Facts," 1984).

The Skylab program (1973-74) was America's first attempt to test whether humans could live and work in space for extended periods of time. The astronauts on the three Skylab missions spent a total of 171 days in outer space. Because the size of the space station allowed astronauts to move around inside the craft to a degree never before possible, clothing became an important factor in the weightless environment and IVA clothing was added to astronaut's wardrobes (Watkins, 1995).

Today, shuttle crew members still use pressurized suits, but only during launch and entry. In the event of a pressure leak in the space shuttle's flight cabin, the suits would maintain a positive air pressure around the astronaut. This provides enough air pressure for the astronaut to survive the return to Earth during an emergency landing. Should an astronaut be forced to bail out over cold water, the pressurized suit would also provide thermal protection (“Space Wear,” 2003).

IVA clothing is not required to comply with the rigid protection requirements of pressurized clothing or Extravehicular (EVA) clothing, which is worn outside the spacecraft, and therefore is similar to normal clothes that provide functionality and comfort in performance.

Current Clothing Systems

The clothing systems for ISS and Shuttle missions vary only slightly due to the duration of the missions. The space station missions are longer in duration, lasting months as opposed to shuttle missions which last a matter of days or weeks. Both types of missions use COTS garments available in the market. Custom clothing would better meet requirements, but would drive up costs and limit availability.

Space Station Clothing

International Space Station (ISS) crewmembers select wardrobe items from the Joint Crew Provisioning Catalog (JCPC) months before they are scheduled to launch. The catalog consists mainly of 100% cotton knit clothing (Joint Crew Provisioning Catalog, 1999).

Astronaut crews do not change clothes as often as people do on Earth, mainly because it is relatively expensive to take supplies into space and there is currently no means of washing clothing aboard the space station. Fortunately, clothes do not get as dirty on the Space Station as they do on Earth for two reasons. Astronauts on the Station live in a controlled environment where the temperature stays at a constant, comfortable level. And, because of the weightless environment, they also do not exert themselves as much physically, unless they are exercising ("Astronauts' Dirty Laundry," 2003).

Space Station crews typically change their work shirt, pants, or shorts every 10 days and get one pair of shorts and a t-shirt for exercising every three days. Underwear and socks are changed every other day and they also get two sweaters ("Space Wear," 2003).

When a piece of clothing has been worn as many times as possible, it is placed in a bag for disposal. Very little clothing is brought home by space station crewmembers. Most of it is eventually placed in an unmanned Progress resupply vehicle before it undocks from the space station. The dirty clothing and other garbage then burns up with the Progress when it re-enters the Earth's atmosphere (“Space Wear,” 2003).

Space Shuttle Clothing

Like space station crewmembers, shuttle astronauts choose their IVA clothing months before their launch. Unlike space station crewmembers, however, shuttle astronauts bring a change of clothes for every day of their mission. Space shuttle crewmembers can choose to wear pants or shorts depending on what they're doing aboard the shuttle and the temperature inside the spacecraft. They also have the option of wearing long or short sleeve polo shirts or rugby shirts, as well as sweaters and pullovers. Like space station crews, shuttle astronauts wear shorts and T-shirts when they exercise. The pants they wear are covered with pockets and Velcro to help keep tools near them. Clothes are stowed after use and returned to Earth with the shuttle (“Space Wear,” 2003).

Specific Clothing Items

For the most part, the selection of clothing provided for the crewmembers for ISS and Shuttle missions is about the same. Table 1 lists specific IVA clothing items that are typically used by astronauts. In general all main clothing items are a selection of COTS garments and must be at least 95% cotton (A. Whitaker, personal communication, January 2004). Astronauts are given a variety of garments to select from in order to provide comfort over a wide range of temperatures and activities.

Table 1. Typical IVA Clothing Selection

ITEM	GARMENT USED
Tops	
Sleep shirt	100% cotton navy blue short sleeved T-Shirt without a pocket made by Hanes.
T-shirt	100% cotton white V-neck T-Shirt made by Jockey.
IVA shirt	At least 95% cotton with remaining material to be polyester or Lycra. Either long sleeve or short sleeve shirts in colors and styles selected by the crewmember from Eddie Bauer, L.L. Bean, Land's End, or J. Crew are acceptable.
Sweater	At least 70% cotton with remaining material to be polyester or Lycra. Style and color selected by the crewmember from Eddie Bauer, L.L. Bean, Land's End, or J. Crew are acceptable.
Jacket	100% FR cotton with removable liner. Liner can be worn as a vest.
Bottoms	
Athletic shorts	These shorts are to be used for exercise only, not as a main clothing item. They are nylon running shorts that can be worn with or without bike shorts.
Shorts	Shorts are made of 100% cotton with two side pockets, one hip pocket, adjustable waistband and Velcro pattern on the legs.
Pants	Trousers made of 100% FR cotton with adjustable waistband, two side pockets, two hip pockets, a zipped pouch and Velcro pattern on the legs.
Undergarments	All undergarments, both women's and men's are unmodified COTS hardware. Currently, the women's items are selected based on each crewmember personal preference. The men's items are a standard vendor and style.
Socks	The crew is allowed to choose from a variety of socks. Slipper socks are a wool blend with leather soles. Polartec socks are made of a polyester fleece material that requires cleaning and "shaving" preflight. The tube socks are a 70% cotton blend. The crew socks are a 70% cotton blend fitted sock that range in size.
Accessories	
Gloves	Glove options include deerskin gloves for men and women and a pilot's glove in a summer weight.
Shoes	Athletic running shoes without cleats for use during exercise can be selected from variety of vendors including: Adidas, Asics, New Balance, Nike, and Reebok Shimano cycling shoes with cleats are for use with the ergometer.
Handkerchief	Unmodified COTS item made of 100% cotton in white.

Source: Whitaker, Alana, personal communication, January 2004.

Flammability Issues

Some of the garments (jacket and pants) listed in Table 1 are stated to be flame retardant (FR). However, a March 2003 release of a document soliciting organizations that may be interested in collaborating with NASA to provide astronaut crew clothing, does not specify that clothing be flame retardant. An excerpt from the notice appears below.

> STATUS REPORT
> Date Released: Monday, March 31, 2003
> Johnson Space Center
> Sources Sought Notice: Space Shuttle Astronaut Crew Clothing
>
> *Material Properties*
> All clothing materials require review and approval by NASA Materials and Processes prior to flight. Clothing containing a minimum of 95 percent cotton is recommended based upon the preference for material that would char rather than melt (such as polyesters) if exposed to high temperatures or flash fires. Sweaters must be at least 70 percent cotton. Exceptions to the 95 percent cotton requirement include undergarments worn under other clothing items and nylon athletic shorts provided for exercise only and not as a main clothing item. Exceptions are handled on a case-by-case basis through the NASA materials review and approval process. Items that are lint producing are washed and tumbled multiple times, followed by shaving, if necessary, to decrease the amount of lint particles. The vendors will be required to provide similar linting prevention methods prior to delivery as required for their particular items. Products that are antilinting, antistatic and antiodor are encouraged. Other innovations will be considered.
>
> Source: Johnson Space Center. (2003). *Sources Sought Notice: Space Shuttle Astronaut CrewClothing*. Retrieved August 25, 2004 from http://www.spaceref.com/news/viewsr.html?pid=8604.

Through communication with NASA personnel, it was determined that FR clothing was dropped from the program due mainly to complaints from astronauts about comfort. Most of the clothing items are cotton or a large percentage of cotton due to the preference for a material that would char rather than melt if astronauts were ever exposed to high temperatures or flash fires. Synthetic clothing is not preferred due to the belief that it may cause more severe burns than clothing with natural fibers like cotton. The use of Nomex (flame resistant) clothing is also currently not accepted by NASA for comfort reasons. They believe heavy Nomex materials will make exercise and other important crew activities very difficult to perform. The Flight Crew Equipment Office at NASA has conducted research indicating that there is no easy solution to finding crew clothing which combines comfort and flame retardancy in the commercial apparel industry (A. Drysdale, personal communication, June 2004).

Fire Hazard Assessment

The oxygen-rich environment inside the space shuttle creates a fire hazard, especially on a long-term basis, such as a mission to Mars, where breakdowns that could possibly lead to a fire have a greater chance of occurring. However, according to a NASA research publication, "the probability of a serious fire event occurring in a given space mission is very low" (Friedman, Jackson, & Olson, 2000, p. 1). Fire prevention on-board the shuttle is supported through the use of carefully selected and tested fire-resistant materials. Good materials selection and stringent flammability control of materials used inside the shuttle does not warrant the use of flame retardant clothing (A. Drysdale, personal communication, June 2004).

In the highly unlikely event of an open fire inside the module, protocol calls for the crew to completely isolate the module until the fire is extinguished. Hence, flame retardant clothing to fight an open fire is not required. Used clothing items are stored in non-flammable containers (A. Drysdale, personal communication, June 2004).

Problems with Current Clothing

ISS missions, which are long in duration, provide a good basis of comparison for how IVA clothing may perform during a long duration Mars mission. The problems that occur with clothing during ISS missions will most likely be magnified on a mission to Mars. NASA can learn from the experiences of the ISS missions to help guide in clothing selection for a Mars mission. IVA clothing has had a significant impact on mission mass and total waste mass for LDSF.

Inspection of the space shuttle upon return from ISS missions reveals a great deal of waste is generated into the zero or microgravity environment of the vehicle. Analysis of the debris from air filters reveals that fiber dislodged from cotton clothing, towels, and rags used during the trip makes up a large proportion of the debris. Lint fiber remains suspended in the air as waste matter which deters operations. Many ISS flight programs have had problems with airborne particles. The debris has caused smoke detector problems, blocked air flow, and overheating of avionics equipment (Drysdale, Garton, & Hasselbrack, 2003).

IVA clothing supply has a significant impact on mission mass for LDSF, accounting for almost 18%. For a Mars mission, 9,000 kg of clothing is required for a crew of six. The supplied clothing, when disposed of, makes up 12% of the total waste mass, making it the largest waste impact. The clothing subsystem has a greater impact on both supply and waste processing than does any other subsystem (The Boeing Company, 2002). For short duration missions, clothing stowage is trivial. For a Mars mission, the mass and volume of clothing to be supplied and stowed is quite significant. Lighter and less bulky clothing would reduce the logistics cost.

Review of NASA Documents

A review of various NASA documents indicates that IVA clothing has not been recognized as a critical element of space exploration.

Johnson Space Center Documents

The Johnson Space Center (JSC) leads NASA's flight-related scientific research efforts and issues technical reports based on their findings. Both the JSC-28484 and JSC-27301D documents cover requirements for equipment and materials, but make no mention of clothing materials specifically. Finally, the JSC 47804, Advanced Life Support Baseline Values and Assumptions Document, states “Clothes are not traditionally part of an environmental control and life support system” (Hanford, 2002, p. 88).

Habitability Documents

Habitability documents are papers published by NASA that document the effects of LDSF on performance, habitability, and workload, and identify and assess potential tools designed to address these issues. The most recent habitability document, Habitability and Performance Issues for Long Duration Space Flight (Whitmore, McQuilkin, & Woolford, 1997), does not cite clothing as an influence on performance. The Habitability Data Handbook Volume 5: Garment and Ancillary Issues (NASA Manned Spacecraft Center, 1971), published over 30 years ago, provides the most thorough evaluation to date of space garment candidates, designs, and fabric considerations.

The Habitability Data Handbook, though largely outdated, serves as a good preliminary review of past practices and clothing requirements. Each section in the Handbook addresses different issues for clothing design and selection.

Section 1. The first section provides an introduction and overview of the purpose of the Handbook. The Handbook is meant to provide criteria by which crew garments may be evaluated for used in manned missions.

Section 2. General requirements for determining the type of material to select for garment construction and the number of wardrobe items is presented. Data must be provided on the following before garment definition:

Mission profile

- Mission duration
- Number of crew members
- Atmosphere (with total pressure)
- Temperature (minimum and maximum)
- Maximum dew point temperature
- Gas ventilation velocity

Crew data

- Metabolic rates during exercise, duty, and sleep
- Crewmen physical sizes in percentile
- Garment wardrobe weight and volume limits

Section 3. This section presents garment style concepts and provides a method for determining the type of wardrobe required (disposable or reusable) based on requirements from Section 2. It covers the advantages and disadvantages of one-piece and two-piece garments as well as sketches for these designs, possible designs for garment openings including pockets, collars, and cuffs, advantages and disadvantages of knit and woven shirts and briefs, headgear and footwear concepts, as well as laundry system trade-off considerations.

According to the Handbook, the number of clothing articles in a basic space wardrobe is a function of allowable weight, allowable volume, personal preference, and hygienic standards. An earth garment change cycle is desirable. These requirements are similar to the current standards and practices at NASA.

Section 3 includes a list of candidate garments for each wardrobe item based on requirements. For example, the IVA shirt candidates are cotton, cotton-dacron, cotton-nylon, PBI, and X400. A cotton knit is the garment recommended due to its comfort, absorbency, appearance, warmth, and antisnag properties.

Section 4. Additional fabric items to consider are presented in Section 4. These include napkins, wipes, and bedding.

Section 5. This section includes analytical data about the thermal aspects of clothing by looking at body heat rejection and the areas of the body that need more insulation. The report recognizes the value of providing thermal comfort to the wearer and selects and evaluates clothing on this basis. Materials evaluated include cotton, nylon, polyester, Teflon, Nomex, and Dacron. The report also covers electrostatic performance, wrinkle/shape recovery, material structural properties, and shrinkage and laundering test results.

This report provides a good framework for clothing selection and evaluation. However, while the material choices are justified in the report, fiber and fabric technology has advanced in the past 30 years, offering updated options for evaluation.

Isolation Experiments Report

Reports of Isolation Experiments (Lane, Sauer, & Feeback, 2002), chamber studies done to advance technologies and methodologies by testing potential solutions to issues related to a closed living environment, also do not treat clothing as a crucial element. Participant evaluations following the isolation experiments include only one question asking subjects to rate the overall acceptability of clothing. No specific clothing issues are addressed.

NASA Standard 3000

General clothing design requirements for IVA clothing can be found in the NASA Standard 3000, a document created to define all generic requirements for space facilities and related equipment. The following excerpt describes the clothing requirements according to the Man-Systems Integration Standards or the NASA Standard 3000:

> 11.13.1.3 Clothing Design Requirements
>
> 11.13.1.3.1 General Clothing Design Requirements
>
> All IVA clothing shall be designed to meet the following general requirements:
>
> a. Suitable for the Environment:
>
> > 1. Garments shall be provided to protect the user from the full range of anticipated working and off duty environments in the space module.
> >
> > 2. Garments to be used in microgravity or partial gravity shall incorporate features that make the garment suitable for use in these environments.
>
> b. Comfort and Freedom of Movement-Wearing comfort and freedom of movement shall be emphasized in the design of the garments and selection of garments.
>
> c. Wearer Effects-The effects from the wearer's body heat generation, skin and hair flaking and loss, and perspiration shall be considered in the design of the garments and selection of materials.
>
> d. Materials and Fabrics-Garment materials shall be selected taking into account the following factors: similarity to Earth garments, flammability, comfort, chemical stability, moisture absorption, water compatibility, tensile strength, abrasion resistance, flexural endurance, wrinkle/shape recovery, cleaning compatibility, electrostatic performance, crease resistance, and freedom from linting.
>
> e. Sizing-The range of sizes available shall be sufficient to provide adequate fit and comfort for the crewmember population without resorting to personalized, custom-fitted garments.
>
> (NOTE: Microgravity or spatial gravity anthropometric changes must be accommodated.)
>
> f. Exclusive Use-All crewmembers shall be provided with garments for their exclusive use.
>
> g. Unassisted Donning/Doffing - All garments shall be capable of being donned/doffed by a crewmember unassisted in normal and emergency situations and operational environments (Emergency mode donning/doffing should preferably use the normal mode closure and fastener).

h. Off-the-Shelf Garments-Off the shelf, commercially available garments shall be used if possible.

i. Personal Preferences-Provide garment options that allow crewmembers to select various styles, combinations of garments, different colors and different pocket styles and cuffs.

j. Aesthetics-Garment aesthetics and overall appearance shall be a very important design factor.

k. Outerwear Hazards-All outerwear garments shall be free of loops, straps, and other obstructions that can snag on equipment.

l. Inner Surface Hazards-An inner surface of garments shall be free of items which can impede free movement, scratch or chafe the wearer.

Source: National Aeronautics and Space Administration. (1995, July). *Man-Systems Integration Standards*. *NASA Standard 3000*.

The NASA Standard 3000 includes an explanation of clothing guidelines, but does not provide rigid requirements or measurable performance levels for IVA clothing. The document recommends vague clothing properties such as comfort, moisture absorption, tensile strength, abrasion resistance, electrostatic performance, and freedom from linting, however, it gives no indication of the relative importance of these properties or what level of performance the garment should attain for each property.

Review of Related Commercial Standards

Two categories of commercial product standards have been identified that may be relevant to IVA clothing for space travel. These standards, shown in Table 2, have been selected to help identify appropriate categories for testing as well as establish possible performance levels for IVA clothing. The performance levels specified in certain ASTM and NFPA standards provide guidelines for needed levels of performance.

The National Fire Protection Association (NFPA) has standards that require strict levels of protection, durability, and other performance categories for different types of firefighter's clothing (National Fire Protection Association, 2004). The American Society for Testing and Materials (ASTM) has identified performance requirements and set standard levels of performance for most categories of consumer apparel products. The ASTM standards are intended as a guide, used purely on a voluntary basis, to aid producers, users, consumers, government and academia (ASTM International, 2004).

Table 2. Related Commercial Standards

	NFPA 1977 Wildland	NFPA 1999 EM	NFPA 1975 Station/ Work Uniforms for Fire Fighters, 1985 Ed.		ASTM Standard Performance Specs			
Material Property (Method)			**Woven Trousers/ Jackets (Shirts)**	**Knit Tee (Sweat) Shirts**	**F 1002 Protective Clothing Non/Coated (shirt/pants)**	**D 4109 Type I (Type II) Wovens**	**D 3995 Knit Career Apparel Dress (vocational)**	**D 4156 Knitted Sportswear Fabrics Shear (Non)**
Fabric Structure								
Fabric Weight (oz/yd^2) *(ASTM D 3776)*			5.5 (4.0)	3.0 (7.0)				
Durability								
Tensile Strength, Grap (N /lb) *(ASTM D 5034)*			50 (20)	-	223N/ 334N 50/ 75 (134N/ 223N) (30/ 50)	308N (178N) 70 (40)		
Tensile Strength, Grap N (lbf) *(ASTM 751)*		135N 30						
Tear Strength N/ (lbf) *(ASTM D. 1424/ 2262*)*	22N 5		5.0 (2.0)	-	22N/ 45N/ 5/ 10 11N/ 22N (2.5/ 5)	13N 3.0 (11N) (2.5)		
Tear Strength N (lbf) *(ASTM D 5598)*		36N 8						
Puncture Propagate Test N (lbf) *(ASTM D 2582)*		25N 5 ½						
Seam Efficiency N (lbf) % *(ASTM 1683)*	Major 315N 70 Minor 225N 50		75% (75%)	75% (75%)				
Seam Efficiency N/mm(lbf/in) *(ASTM 751)*		67N/ 50mm 15/2”						
Yarn Slippage N (lb) *(ASTM D 434)*					only for shirts (6mm@134N) (0.25” @30)	6.3mm@133 N (111N) 0.25@30 (25)		
Burst N (lbf) (ASTM D 3786)			-	35 (50)		-	267N 60 (60)	133N (222N) 30 (50)
Burst kPa(psi) *(ASTM 751)*		345kPa 50						

Table 2. (Continued)

Material Property (Method)	NFPA 1977 Wildland	NFPA 1999 EM	NFPA 1975 Station/ Work Uniforms for Fire Fighters, 1985 Ed.		ASTM Standard Performance Specs			
			Woven Trousers/ Jackets (Shirts)	Knit Tee (Sweat) Shirts	F 1002 Protective Clothing Non/Coated (shirt/pants)	D 4109 Type I (Type II) Wovens	D 3995 Knit Career Apparel Dress (vocational)	D 4156 Knitted Sportswear Fabrics Shear (Non)
Protection								
Flammability *(CFR 1610)*						Pass	Class 1 or 2	Pass
Flammability (in. char, after flame) *(Fed-STD-191A/ method 5903)*	100mm 4” char, 2 sec after flame, no drip		6” 2 sec.	6” 2 sec	127mm 5/ 5 3/ 3 sec 152mm (6/ 6) (5/ 5 sec) no melt or drip			
Heat/ Thermal Shrinkage Resist (%) *(NFPA 1977:6.4)*	10							
Total Heat Loss *(ASTM F 1868)*	450W/m^2	450W/m^2						
Radiant Protect Perform (RPP) *(NFPA 1977:6.2)*	8							
Liquid tight Integrity *(ASTM F 1359a)*		no penetration allowed						
Biopenetratio n *(ASTM F 1671)*		no penetration allowed						
Water Repellency *(AATCC 22)*		70 spray rating						
Performance								
Dimensional Change (%) *(AATCC 135*)	5		3 (3)	5 (5)	-- (3/ 3)	2-3 (2-3)	2-3 (2-3)	2-3 (2-3)
Fabric Appearance DP *(AATCC 124)*						3.5 (-)	4 (3)	3.5 (3.5)
Colorfastness to Laundering (shade/ stain)			3 (3)	3 (3)	-- (3/ 3)	4/ 3 (2/ 2)	4/ 3-4 (4/ 3-4)	4/ 3 (4/ 3)

Table 2. (Continued)

Material Property (Method)	NFPA 1977 Wildland	NFPA 1999 EM	NFPA 1975 Station/ Work Uniforms for Fire Fighters, 1985 Ed.		ASTM Standard Performance Specs			
			Woven Trousers/ Jackets (Shirts)	Knit Tee (Sweat) Shirts	F 1002 Protective Clothing Non/Coated (shirt/pants)	D 4109 Type I (Type II) Wovens	D 3995 Knit Career Apparel Dress (vocational)	D 4156 Knitted Sportswear Fabrics Shear (Non)
(AATCC 61)								
Colorfastness to dry cleaning *(AATCC 132)*					-- (3/ 3)	4 (3)	4 (4)	4 (4)
Colorfastness to Crocking (dry/ wet) *(AATCC 8)*			3 (3)	3 (3)		4/ 3 (3/ 2)	4/ 3 (4/ 3)	4/ 3 (4/ 3)
Colorfastness to Perspiration (shade/ stain) AATCC 15						4/ 3 (3/ 3)	4/ 3 (4/ 3)	4/ 3 (4/ 3)
Colorfastness to Xenon Arc Light *(AATCC 16E)*			20AFU Step 3 (20 AFU Step 3)	20 AFU Step 3 (3)		20AFU Step 4 (4)	40/20AFU Step 4 (4)	40AFU Step 4 (4)
Burnt gas fumes (AATCC 23)						Class 4	Class4	Class 4

Source: Barker R., Scruggs, B., Thompson, D., Fratto, L. (2003, November 4). *Annual Report: Clothing Impacts on Equivalent System Mass*. The Boeing Company.

Working in Weightlessness

An understanding of the unique environment as well as the body issues faced by astronauts provides a better understanding of the types of garments and garment materials that would best suit their needs.

Environment

The space shuttle is generally a comfortable place to live. The humidity is low and the temperature is moderate. During a normal shuttle flight, the inside temperature is about 68 degrees Fahrenheit. Space craft environments are also extremely dry (Space Science Group, 2004).

Body Changes

Working in a weightless environment causes the body to change in ways that may affect clothing selection. Without gravity, the barrier that normally prevents fluids from passing through blood vessels into surrounding tissues on Earth becomes ineffective. Therefore, fluids in the body shift upward. The astronauts develop flushed, bloated faces and upper bodies while their legs and hips become thinner (Graham, 1995). The "puffy face, bird legs" syndrome, as it is called, causes the astronaut's shirts to become snug while the pants become too large (Watkins, 1995).

Weight loss is also a problem that occurs mainly during the first few months of long duration space flights due to fluid loss and loss of appetite. Weight loss can differ depending on the amount of time spent in space. Astronauts on Skylab 2 lost three to six pounds during their one month stay. On Skylab 3, astronauts stayed twice as long and lost a comparable amount. On Skylab 4, the astronauts lost mass during the first 10 days, held their own for the remaining 74 days, and even gained some back towards the end (Stern, 2001).

There is a major loss of bone density in the legs and the spine while in space. This occurs in microgravity because the body has no need to maintain its skeletal structure to Earth-normal standards. Therefore, bone tissue is absorbed and not replaced. Astronauts may lose up to 1% of their bone mass each month. This loss of bone causes high calcium levels elsewhere, which can lead to kidney stones (Hullander & Barry, 2001).

While in space, the spinal column expands. The spaces between the vertebrae in astronaut's spinal cords elongate. This causes astronauts to grow 1-2 inches taller (Watkins, 1995). It can also cause backache and nerve problems. The heart and other muscles are affected in a zero gravity environment as well. All muscles weaken and shrink. The heartbeat slows and heart tissue shrinks (Graham, 1995).

Activities

Because astronaut's bodies are not getting the resistance they are used to in gravity, astronauts suffer bone and muscle deterioration and therefore must exercise frequently. Exercising also helps the astronauts readjust more quickly to Earth's gravity when they return home. Astronauts participate in a planned exercise program to counteract the effects of the environment. Flight doctors recommend about an hour of exercise a day for long duration missions (Hawkey, 2003).

The astronauts seem to sweat heavily during their workout sessions. Moving air from a nearby duct is used to dry off the perspiration produced from exercising. They also have to constantly wipe the sweat off their bodies with towels to keep dry. Otherwise, the sweat would stick to the skin and grow thicker and thicker (Hawkey, 2003).

Functional Design Considerations

Changes in the astronaut's body will affect the fit of their clothing. Their pants become too large and their shirts more snug. Clothing must allow for the expansion of the upper body. Expansion features on the waistline of pants will also help to increase adjustability. Garment sizing should allow for adjustment as body changes from fluid and weight shifts occur. Fabrics with stretch-recovery properties can provide accommodation to these changes (Watkins, 1995).

Without the weight of gravity, loose edges float free and can snag on the interior of the spacecraft. Garments designed to be closer to the body won't snag on the interior of the spacecraft. Astronauts will be donning and doffing their clothing with little or no help. The process of getting dressed is difficult without the pull of gravity. Clothing that requires little bending, has large openings, and has easily and quickly closed fasteners is best. Tools used to perform tasks need to be secured. Features such as special pockets, loops, or Velcro, can be added to garments to ease the management of devices (Watkins, 1995).

Mars Mission Assumptions and Textile Selection Issues

A manned mission to Mars may not occur until decades into the future, making it hard to devise any specific assumptions about how the mission will operate. However, NASA has some general notions about certain issues that will affect IVA clothing selection. For example, it has been determined that cleaning and reusing clothing would significantly reduce the mass of clothes allotted per mission. Therefore, a project is in process to develop washing machines for space. The clothing would need to comply with this system.

There will most likely be no resupply of clothing materials for a three year, six person Mars mission as they do on ISS missions and space will be at a premium (M. Ivins, personal communication, February 2004). Therefore, the astronauts would have to take all the clothing they needed for a three year mission.

Table 3 details further the issues to consider when selecting textiles specifically for Mars travel. Many of these issues relate to requirements set forth by the NASA Standard 3000. However, they are geared more towards the concerns of Mars travel.

Table 3. Issues for Textile Selection of Mars IVA Apparel

Issues	Consideration
Mass and volume of shipped clothing	For a Mars mission~9,000 kg of clothing (not counting stowage, etc) is required for a crew of 6, using an ISS approach. Lighter and less bulky clothing would reduce the logistics cost. Vacuum packaging would reduce mass and volume.
Processing of clothing and wastes	Supplied clothes will become waste (24m^3 for a Mars mission). Current wardrobes are comprised of a high percentage of cotton, which has 8.5% water regain. Storage and dumping of clothing would have an associated loss of water to the system. For a Mars mission this would approach 1 ton of water loss. Lighter and less bulky clothes would reduce wastes. Lower water retention fabrics would reduce drying.
Bio-hazardous conditions	Minimizing off-gassing and microbial loads from soiled clothing, and improving hygiene. Microbes could also be a problem should there be an increase in cabin humidity levels.
Clothing performance	Heat transfer, moisture transfer, and tactile properties
Contingency-environmental	Clothing needs to provide for crew comfort in the case of changes in environmental conditions
Contingency-fire	Cotton is highly flammable, especially in an oxygen rich atmosphere. Some synthetic polymers may melt and drip. Others are more heat resistant.
Durability	Wardrobe/laundering approach must remain functional for duration of mission. More robust fabrics will produce less waste and require less frequent replacement.
Ease of care	Should be compatible with cleaning methods being considered, as well as being soil resistant and not require pressing
Fit	Clothing needs to accommodate changes in weight, height, posture, and body shape due to micro-gravity conditions and possible calorie imbalance.
Functionality	Fire safety, protection from abrasions, pockets and loops for securing tools, etc.
Human factors/crew acceptability	Attractiveness, comfort and fit, and utility will affect crew acceptance. Aesthetic qualities of clothing will impact mood-critical in isolation.
Lint	STS had airflow problems due to lint buildup on filters. Choice of fabric has a major impact on linting.
Static	Static problems depend on fabric selection and humidity.
Sweat loss	Could double water loss to system if clothing is disposed of without drying (~1.5 tons). Low moisture content fabrics could reduce this loss.
Treatments	Anti-microbial, wetting agents, wicking agents, softeners, odor control, static control (permanent vs. recurring), soil release

Source: The Boeing Company. (2002). *Analysis & Modification of Clothing to Reduce Impacts on the Waste Subsystem as Measured by ESM.*

Definition of IVA Clothing Requirements

With a view of astronaut needs and environmental considerations, and a review of commercial standards as well as issues related to textile selection, recommended performance categories for IVA clothing were developed. Categories for fabric evaluation include durability, safety, comfort, appearance, care, weight, and waste generation (Barker, Scruggs, Thompson, & Fratto, 2003). A description of these requirements is provided below.

Durability

Durability of IVA clothing is important for long duration flights. The garments are expected to be worn, cleaned and reworn many times. Garment fabrics need to be strong enough and tough enough to withstand wear as they will be worn throughout work, exercise, and cleaning cycles.

Safety

The clothing should provide safety and protection. Since IVA clothing is for inside use, protection for extreme environments outside the space vehicle is not required. However, there are other safety protection issues for the indoor IVA garments. In the oxygen-rich environment, fire protection is a consideration. It is advisable to make the clothing of fibers that are slow burning and do not melt, but the benefits and risks need to be assessed which may require making some trade-offs.

Antistatic clothing will reduce the risk of sparks and ignitions resulting from build up of static charges. Electrostatic charges that may cause fabric to cling to equipment or other surfaces may be deterrent to functionality. The fabrics should also be antisnag to prevent them from getting caught on machinery.

Hygiene is an important safety consideration. Anti-microbial fabrics that retard microbial growth and prevent odor are desirable. Prevention of odor is important, especially when garments are worn for days before being changed.

Comfort

The astronauts need to be able to perform tasks efficiently in the selected clothing. Clothing should not impede work productivity. It should not be restrictive to the body in bending or stretching and should allow astronauts to perform tasks and exercises. The garments should minimize irritations, rubbing, or chaffing of the skin and the hand should be pleasing, not harsh or scratchy. Garment sizing should also allow for adjustment as body changes from fluid and weight shifts occur. Fabrics should possess stretch-recovery properties to accommodate the changes. Fabrics that transmit heat and wick moisture away from the body as well as breathable fabrics will provide increased comfort and productivity.

Appearance

Appearance is important for these garments that will receive frequent wear and frequent washing. The clothing should be anti-wrinkle and resist fading, pilling, snagging, and shrinking. The astronauts should be able to add personal and mission-related touches to the clothing to individualize the item. Colors should be aesthetically pleasing and garments should coordinate. Aesthetic qualities could impact mood, which is critical in isolation.

Care

Fabrics should be selected that minimize efforts required for cleaning and care of the clothing. Soil repellent finishes will reduce the frequency of care. Fabrics with low moisture absorption require less washing and drying, therefore using less energy and water.

Weight

The clothing needs to be as light in weight as possible and have a low packaged volume in order to reduce mass. Clothing is only allowed a certain percentage of the total mass on the shuttle.

Waste generation

Selected garment materials should be made of fibers that provide low waste generation, or low linting. The current off-the-shelf cotton garments worn by astronauts are shaved and washed to reduce the particulate generation.

Table 4 outlines ideas for possible fibers and fabric treatments for IVA clothing based on identified astronaut needs and performance categories.

Table 4. Potential Fibers and Treatments Based on Clothing Needs

	---------------------------Fabrics---------------------------	
Clothing Need	**Fiber**	**Treatment**
Light weight	Synthetic fibers have lower specific gravity than cotton	
Low waste generation	Fabrics of continuous filament fiber will not generate lint because there is no short fiber to become dislodged from fabric as occurs in cotton fabrics, which are a short staple length fiber	Some finishing applications may reduce linting in cottons or other staple fiber fabrics (singeing, topical chemical applications)
Durability	Requires adequate fiber strength and good abrasion resistance. Synthetic thermoplastic fibers (nylon, olefin, polyester, FR Nomex, aramid and PBI) are stronger, tougher, have good abrasion resistance and long wear life. Cotton and most cellulosic fibers are moderately durable, but will wear out faster than thermoplastics. One exception is Lyocell, a recent development in regenerated cellulose fibers that claims to have strength more comparable to polyester than rayon, which is very weak.	Various chemical finishing treatments used to modify various performance properties of cellulosic fibers typically reduce durability
Safety a) Fire	Flame retardant (FR) variants of various manufactured thermoplastic fibers may be evaluated for applicability in IVA applications	Flame retardant topical chemical finishes may be applied to cellulosic fabrics, but tend to add weight, stiffen, and add harsh tactile hand quality. They may not be durable to washing or cleaning, and may emit chemicals into the environment
b) Health		"Smart Textiles" are garments/ products made from fabric of conductive fibers, connected to body monitoring sensors, and plug into computer circuitry to continuously monitor the vitals that signify body stress.

Table 4. (Continued)

c) Hygienic/ sanitation	Thermoplastic fiber fabrics have less susceptibility to wetness and provide less attractive environment for microbial growth. Silver has been added to some thermoplastic fibers as a microbial inhibitor.	Anti microbial or antibacterial topical chemical finishes may be added to fabrics to retard growth of germs and microbes. Fabrics may be constructed with some silver containing yarns.
Comfort a) Breathable	Cotton, or cellulosic fibers, provide the best moisture absorption and heat conductance for maintaining body thermal comfort in clothing wear attributed to moisture content that is highly conductive. Thermoplastic fibers have low moisture absorption and may be less conductive than celluloses, but there are wicking fiber variants that have compensated for absorbency.	Fabrics of thermoplastic fibers may also be treated with topical chemical finishes that induce wicking when fabric is in contact with liquid sweat.
b) Tactile	Longer, finer cotton fiber has smoother, more pleasant tactile quality than most other fibers. Moisture content of cotton also improves tactility. Micro fiber variants and certain cross section shapes of thermoplastic fibers have pleasant skin tactile quality. Teflon may be incorporated into a fabric at points to impart smoothness where skin chaffing is a problem.	Comfort stretch, provided by knit fabric structure, will have better wear comfort. Topical finishes may be used to enhance the tactile quality of the thermoplastic fiber fabrics. Fiber blend fabrics, especially those containing cellulosic and thermoplastic fibers, may enhance the tactile quality of a garment fabric
c)Adjustable garment fit	Add spandex fiber to the fabric to accommodate body changes during flight.	Knit structure fabrics/ garments require less precise fitting
Care	Thermoplastic fiber fabrics with low absorbency are easier to care for. They repel water-borne stains. Low absorption means little wetting and quick drying, and may be iron free.	Stain resistant topical finishes are added to fabrics to impart better stain/ soil resistance and easy care properties. Nano-Care is a new technology that imparts the Teflon finish without interfering with fabric softness.

Table 4. (Continued)

Aesthetics	Fabrics of most fibers are dyeable in a range of attractive colors.	Knitted and woven candidate fabrics need to be tested in a variety of laboratory instrument tests, as well as in wear trials to identify those with most aesthetically appealing fiber-fabric for ALS wardrobe.

Source: Scruggs, Barbara, Monthly Report to Boeing, 2003.

Market Analysis of COTS Garments

"Consumers today are looking for materials that control everything…the goal is for the ultimate in terms of performance and comfort" (Walzer, 2004, p. 66). Fortunately, incredible advances in technology have allowed clothing to deliver on this goal and go beyond what was ever thought possible. A market survey of commercially available garments identified a range of modern clothing materials that could potentially enhance the functional performance of IVA wear.

Health Promotion

Wellness is a strong lifestyle trend with textile applications. Performance active wear fabrics and high-tech medical materials have managed to cross paths through a number of health-promoting commercially available textile products.

Holofiber by Wellman is a body-responsive textile fiber that claims to increase circulation and improve strength when worn against the skin. The Holofiber material supposedly modifies the spectrum of visible light, interacting with certain wavelengths, and altering them into energy. When Holofiber is worn as clothing, it transmits the altered energy to the body. This energy sent to the body by Holofiber helps the body's cells to be better oxygenated. It does not have to be subjected to a continuous exposure of light in order to function effectively (Dockery, 2004).

X-Static® is an all-natural fiber with pure silver permanently bonded to the surface. First developed for the US Army, this high performance material is woven with silver fibers, which inhibit the growth of odor-causing bacteria. The natural thermodynamic properties of silver also act as a temperature regulator to keep athletes comfortable in hot weather as well as colder conditions. It has antimicrobial, heat-transferring, anti-static, and therapeutic properties (Dockery, 2004).

Companies all over the world have also recognized a consumer demand for clothes that deliver cosmetic and other well-being benefits. New apparel will be available that includes moisturizers, anticellulite properties, a hair retardant and an ingredient that promotes tanning. An example is Lycra Body Care which uses fiber microencapsulation technology to deliver moisturizing benefits. Moisturizing agents stored in the fiber structure break open and release their contents progressively as garments move against the skin, continuously hydrating it. A gentle massaging action works vitamin-rich nutrients into the skin (Walzer, 2003).

Nanotechnology

Nanotechnology provides the ability to work on a nano or submicron scale to create intelligent structures that are stronger and have fundamentally different, performance-enhancing molecular organizations. This ability "is so flexible, it opens the door to opportunities for the development of new, never-before-seen performance properties," said Renee Hultin, president of Nano-Tex, North America (Dunn, 2003). The nano structures are attached in the fabric form during the finishing stage and are therefore added permanently to the base fabric without infringing on the characteristics of the original material. The result is a hybrid fabric that combines previously unlike properties without having to resort to a topical treatment (Walzer, 2003).

Products currently available from Nano-Tex include NANO-CARE® for stain resistance and liquid repellency on cotton, NANO-PEL™ for breathable fabric that remains liquid and stain repellent, NANO-DRY® to move perspiration away from the body while drying quickly, and NANO-TOUCH™, which gives man-made fabrics the feel and comfort of natural fabrics. Another product designed to capture body odor, NANO-FRESH™, is in the works (Dunn, 2003). With Nanotechnology, common apparel annoyances like stains, odors, wrinkles, fading and static cling will all soon be things of the past (Walzer, 2003).

Moisture-Management Athletic Apparel

There is a large category of new high performance synthetic fabrics developed for athletic apparel. They contain absorbing and wicking properties that move body moisture and heat away from the skin to keep the person dry and comfortable and control odor. New standards for comfort are being achieved with these lightweight, stretchy materials that wick and feel soft next to the skin. Long a priority technical feature, new moisture management materials now offer bone-dry performance as opposed to the sweat-soaked cotton T-shirt (Walzer, 2003).

In recent years, this category has gone from purely underwear to technical shirting and even street wear. The category has exploded in the last decade from just a few offerings to a proliferation of products (Walzer, 2003). Examples include Nike Dri-Fit, Champion Double Dry, Russell Dri-Power, NFL Equipment/Reebok Play Dry, Under Armour, and COOLMAX® Performance Fabrics.

Treatments once applied topically are now inherent in the fiber, making for long-lasting performance that doesn't wash off with time. Suppliers have greatly diversified their offerings to include a variety of weights, surface treatments and blends (Walzer, 2003).

Fire Retardant Clothing

The wearability of fire-retardant garments has greatly improved over previously available items as garment manufacturers continue to develop new styles. New FR clothing designs are more durable and comfortable than ever before, resembling everyday clothing (Randy Wade Sr., 2004). Although fire resistance is not a requirement for IVA apparel, improvements in wearability make this category an appropriate candidate for consideration.

Tencel®

Tencel is a regenerated cellulosic fiber made from a processed wood pulp that is extremely strong in both its wet and dry states. In fact, Tencel is stronger than other cellulosics, including cotton, and approaches the strength of some of the stronger polyesters. It is soft, breathable, lightweight, machine washable, resists wrinkling and dries quickly. Tencel also has a high moisture regain and the hand of silk. With renewed interest in natural fibers and the fusion of fashion and active apparel, Tencel is becoming trendy and many producers are blending it with cotton, linen and synthetics (Balin, 1998).

High-Tech Wool

Today's new technical wools boast a number of functional features such as breathability, water resistance and moisture transfer properties. Products are also lighter in weight, don't itch, and can endure machine washing and drying without shrinking or losing any inherent features (Walzer, 2000).

Smart Textiles

Many fashion experts say clothing in 10 to 20 years will be interactive, more functional than ever, and tailored to a consumer's personality and body chemistry rather than designed for looks. Smart Textiles are garments made from conductive fibers woven into fabric, enabling clothes not only to cover the body but to be a personal assistant and provide advanced body protection. They are able to sense electrical, thermal, chemical, magnetic or other stimuli from the environment and adapt or respond to them, using functionalities integrated into the textile structure. For example, they can be connected to body monitoring sensors, and plug into computer circuitry to continuously monitor vitals. These garments of the future will clean and mend themselves, grow or shrink to fit a variety of shapes and sizes, change colors and adjust the temperature according to wearer needs (Tippit, 2000).

Phase Change Materials

Phase change materials (PCMs) store, release or absorb heat as they change from solid to liquid form, giving off heat as they change to a solid state and absorbing it as they return to a liquid state. These materials are now finding their way into textile products (Mansfield, 2004).

PCMs in the form of microcapsules can be incorporated within fibers or coated onto fabrics. When the encapsulated PCM is heated to the melting point, it absorbs heat energy as it moves from a solid state to a liquid state. This phase change produces a temporary cooling effect in the clothing layers. If the PCM garment is worn in a cold environment where the temperature is below the PCM's freezing point, the microencapsulated liquid PCM will change back to a solid state, generating heat energy and a temporary warming effect. This heat exchange supposedly produces a buffering effect in clothing, minimizing changes in skin temperature and prolonging the thermal comfort of the wearer (Mansfield, 2004). Textile PCM products available in the market include ThermoSense by Duofold.

CHAPTER III

RESEARCH METHODOLOGY

Purpose

The purposes of this study are to evaluate and recommend materials for use in astronaut's IVA wardrobes based on the needs and requirements of LDSF, and to develop a model that would allow NASA to systematically select appropriate garments for IVA clothing applications. The objectives of this study are as follows:

1. Collect information on astronaut and environmental needs as well as NASA and related standards and practices.
2. Define the performance requirements for IVA clothing.
3. Perform a market survey of COTS materials that could potentially meet requirements and represent the latest in textile innovation.
4. Select candidate garments whose performance claims best match IVA requirements.
5. Identify the test methods best suited to measure the critical performance categories of each garment.
6. Test candidate materials according to standardized test procedures in order to verify performance characteristics.
7. Evaluate the performance of each garment as compared to others and recommend the candidate garments that best meet requirements and rate highest on performance and user priorities for IVA use.
8. Use the above results and processes to develop a model for NASA to guide in future selection of IVA clothing.

Research Design

This study involves the collection of both primary and secondary data, and will be conducted in two parts. Watkins's functional design process has been adapted to this study, as shown in Figure 3, and serves as the conceptual framework for accomplishing each research objective.

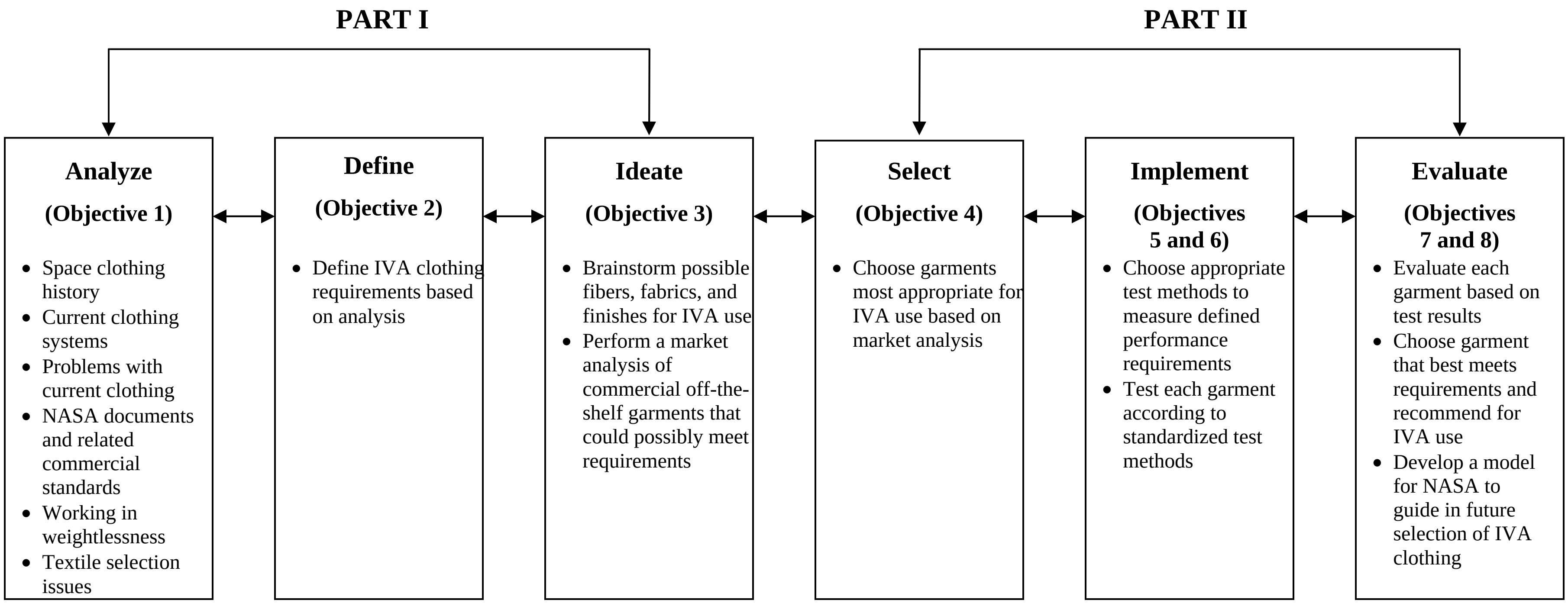

Figure 3. Research Design

Adapted from "The Design Process" Watkins, Susan M. (1995). *Clothing: The Portable Environment* (2nd ed.). Ames, IA: Iowa State University Press.

Part I

Part I of this research (analysis, definition, and ideation) involved gathering information on astronaut needs and activities, NASA practices and standards, as well as defining requirements and searching the market for possible solutions. This data, presented in Chapter II, provides a framework for data collection in Part II.

Analyze

Research Objective: Collect information on astronaut and environmental needs as well as NASA and related standards and practices.

The analysis phase of this study, presented in Chapter II (p. 10-48), involved basic exploratory research to help become familiar with the problem and the products users. A literature review of existing research in the area included: functional apparel processes, the history of space clothing, current clothing systems, problems with current clothing, the constraints of working in a weightless environment, and a review of NASA clothing documents and related commercial standards.

The tools used for the analysis phase included:

- NASA and JSC websites, publications, documents
- ASTM and NFPA standards
- Internet research
- Personal communication with NASA and Boeing personnel
- Boeing documents

Through this phase of research, a clearer definition of the wearer needs, issues, and related standards on which solutions should be based was determined.

Define

Research Objective: Define the performance requirements for IVA clothing.

Definition includes a statement of the goals needed to solve a problem. The information collected in the analysis phase was sorted through and the most essential requirements for IVA apparel were determined. Performance requirements, defined more thoroughly in Chapter II (p. 38), included: durability, safety, comfort, appearance, care, weight, and waste generation. A proper definition assures the product is satisfying the needs of the user.

Ideate

Research Objective: Perform a market survey of COTS materials that could potentially meet requirements and represent the latest in textile innovation.

New ideas and design concepts to solve a functional apparel problem are generated in the ideation phase. Because NASA prefers COTS materials as opposed to developing their own, a market survey of textile innovations that could potentially serve as solutions was performed once requirements were defined. The results were presented in Chapter II (p. 44).

The tools used in this phase included:

- Internet research
- Retail in-store research
- Trade literature
- Newspaper articles
- Recommendations from NC State faculty

This phase of research helped determine the possibilities that exist in the universe of new textile innovations on the market that could potentially solve the IVA clothing problem.

Part II

Part II of this research (selection, testing, and evaluation) involved testing garment materials that were selected based on the requirements defined in Part I. Each garment was tested using standardized test methods chosen to measure appropriate characteristics of the fabrics. Results from the tests helped determine which garments are best suited for IVA applications. Finally, a model was developed to help guide NASA in selecting clothing for future IVA applications.

Select

Research Objective: Select candidate garments whose performance claims best match IVA requirements.

In the selection phase, commercially available garments were chosen for individual evaluation based on their ability to meet the requirements. While the current IVA wardrobe consists of sweaters, jackets, t-shirts, pants, undergarments, socks, and athletic shorts, the IVA t-shirt was chosen as a representative focus garment for this study. Therefore, efforts to select garments in the targeted COTS materials focused only on those high-tech textile innovations available in a t-shirt form.

Each garment was carefully chosen for its ability to satisfy the needs of astronauts as well as NASA and Mars mission requirements. A 100% cotton white t-shirt made by Jockey was chosen as the control garment as it most closely resembles the IVA t-shirt currently worn by astronauts. A summary of the ten garments chosen for testing follows. Table 5 provides further detail of the fiber content and specific manufacturer's claim for each garment based on hang tags and garment labels.

Two 100% combed cotton garments. The control garment is a plain cotton t-shirt. This garment will provide a benchmark for testing other items. A heavier 5.8 oz cotton jersey was also tested due to its performance claims over the control garment. The Land's End Super-T claims to be unshrinkable, durable, and fade resistant.

Two high performance polyester wicking shirts. Both are competitive in the marketplace and make similar performance claims to wick perspiration from the skin to the outer layer of the garment, allowing the body to regulate its temperature and keeping the body dry and comfortable.

A garment that promotes the health of the wearer. Holofiber claims to work with the body's own energy system to increase blood oxygen levels and actually enhance the ability of the body to build strength, accelerate muscle recovery and regulate body temperature. The garment also claims to reduce the chances of cramping, swelling and muscle fatigue.

A Nomex shirt. This garment resists ignition and will not continue to burn when removed from the ignition source. Designed for continuous wear, this garment meets the performance requirements of NFPA 70E (2000 Edition) and ASTM F1506-00 and is acceptable under OSHA Final Rule 1910.269.

Two garments that claim to inhibit bacterial growth and provide wicking capabilities. The Medalist garment contains X-Static® silver fibers and a moisture transport system. X-Static® is an all-natural fiber with pure silver permanently bonded to the surface that has antimicrobial, heat-transferring, anti-static, and therapeutic properties. The Domestic Fabrics Wick-a-Way garment is also a wicking garment that has been constructed using an antimicrobial yarn.

A performance wool garment. The Wickers Wool T-shirt claims to prevent perspiration from beading up on the skin, keeping the body dry. This technology is combined with wool's unique ability to move moisture through the fabric and evaporate it into the air. The garment also claims to be resistant to odors. According to the manufacturer, test garments have been worn, exercised in, and not washed for up to 10 consecutive days without any perceptible odor. It is also made up of 50% FR Viscose.

A Tencel® garment. Tencel® is a regenerated cellulosic fiber, like rayon, that is extremely strong in both its wet and dry states. It is soft, breathable, lightweight, machine washable, resists wrinkling and dries quickly. Tencel also has a high moisture regain.

Table 5. Detail of Garments Chosen for Testing

Item	Description	Fiber Content/Care	Manufacturer's Claims
A	Jockey Classic Crew Neck Short Sleeve T-shirt	100% combed cotton, Made in the USA	Premium, super-absorbent, 100% combed cotton knit Natural stretch for a custom fit that moves with you Maintains its shape Tagless label for comfort
B	Under Armour Loose Gear Crew Neck Short Sleeve T-Shirt with Side Panels	Body: 100% polyester Panel: 79% cat poly, 21% elastane Made in Honduras Care: machine wash warm with like colors, do not use softeners, tumble dry low, do not iron, do not bleach	Wicks perspiration from your skin to the outer layer of the garment, allowing your body to regulate its temperature in any condition or climate A generous cut and smooth, silky finish for the ultimate in cool comfort
C	Nike Dri-Fit Crew Neck Long Sleeve T-Shirt	100% polyester Made in Mexico Care: machine wash warm with like colors, do not bleach, do not use softeners, tumble dry low, cool iron, do not dry clean	Moves moisture away from skin Keeps you comfortable longer
D	Holofiber Crew Neck Short Sleeve T-Shirt	92% polyester, 8% lycra Made in U.S.A Care: machine wash warm, tumble dry cool, no bleach, no iron, no fabric softeners	The benefits of Holofiber are produced by increasing oxygenated blood flow throughout the body Helps build strength Accelerates muscle recovery Regulates body temperature
E	Bulwark Nomex Long Sleeve Henley Shirt	100% Nomex IIIA Flame Resistant ARC rating 6.8 ATPV Made in Mexico Care: dry clean or wash at temperatures not to exceed 140 degrees F, no chlorine bleach	Constructed from flame resistant fabrics and components, resists ignition and will not continue to burn when removed from the ignition source. Designed for continuous wear, this garment meets the performance requirements of NFPA 70E (2000 Edition) and ASTM F1506-00 and is acceptable under OSHA Final Rule 1910.269. Not intended for fire entry or structural fire fighting activities and provides no personal protection from chemical exposures. Remove garment at once if fouled with flammable material.

Table 5. (Continued)

F	Medalist Dri-Max (w/X-Static) Power-Gear Crew Neck Short Sleeve T-Shirt	97% polyester, 3% X-Static Made in the USA Care: machine wash warm, gentle cycle with like colors, no bleach or fabric softener, tumble dry warm on gentle cycle, iron if necessary, use low cool setting	MicroSkin Compression Stretch**,** Anti-Bacterial comfort of X-Static Silver fiber**,** UV-UPF protection**,** Pill-proof durability**,** Skinetics Moisture Transport Technology**,** Microfiber comfort**,** Durable FlatSeam construction X-Static is anti-odor (inhibits the growth of bacteria and fungi), thermodynamic (regulates temperature), and anti-static (reduces electrostatic discharge), safe, natural, and lasts for the lifetime of the product
G	Domestic Fabrics Wick-a-Way Plus Fabric	70% Polyester and 30% Cotton	A wicking fabric that has been constructed using an antimicrobial yarn. Provides permanent, safe and effective protection against many different fungi and bacteria, facilitating the reduction and spread of infection. Also pulls moisture away from the wearer's body.
H	Wickers Wool Crew Neck Long Sleeve T-shirt	50% Merino Wool and 50% FR Viscose Made in the USA Can be machine washed in cold water for easy care.	Evaporation technology keeps you more comfortable than other performance garments. Prevents perspiration from beading up on the skin, keeping you drier no matter what your activity. This technology in combination with wools unique ability to move moisture through the fabric and evaporate it into the air makes Wickers Wool garments comfortable through a wide range of weather conditions and activities. Resistant to odors. Test garments have been worn, exercised in, and not washed for up to 10 consecutive days without any perceptible odor, making them perfect for extended outdoor usage. Flame Retardant
I	Land's End Long Sleeve Solid Super-T	100% combed cotton Imported Machine wash	Hearty 5.8 oz combed cotton jersey fabric that's soft yet durable. Fabric is prewashed and unshrinkable. Colors are vibrant and long lasting. Reinforced shoulders and neck

Table 5. (Continued)

			won’t tug out of shape. Side seams prevent the twist typical of tube tees. Straight bottom hem. Bleed-proof dyes resist fading.
J	Tencel® Knit Short Sleeve Crew Neck T-shirt	100% Tencel®	Feels soft and supple against your skin. It skims the body without ever clinging.

Implement

Research Objective: Identify the test methods best suited to measure the critical performance categories of each garment.

The strengths and limitations of the candidate fabrics were evaluated using a variety of standardized tests. The appropriate test methods to verify critical performance categories were identified and garment materials were tested accordingly. The test methods were chosen based on their ability to measure the requirements defined in Chapter II (durability, safety, comfort, appearance, care, weight, and waste generation). The test methods chosen are shown in Table 6.

Table 6. Test Methods and Descriptions

Test Category and Description (units)	Test Method
<u>Basic Fabric Structure</u>	
Weight (oz/yd^2)	ASTM D3776
Thickness (mm)	KES FB-3 Compression Tester
<u>Durability</u>	
Bursting Strength (psi)	ASTM D3786 Hydraulic Diaphragm Test
<u>Comfort</u>	
Cantilever Bending (bending length & flexural rigidity)	ASTM D1388
Full KES Evaluation (tensile extensibility, shear, bending, compression, and surface roughness)	KES FB-1 Tensile-Shear Tester
Qmax	KES-F7 Thermolabo instrument
Wicking (cm)	Vertical Wicking Test
Heat Loss (watts/ m^2)	Sweating Hot Plate Method (min, comf, and max values)
GATS Absorption and Drying Tests	Gravimetric Absorbency Testing System
<u>Garment Care</u>	
Standard Guide for Evaluating Stain Removal in Home Laundering	ASTM D4265-98
Dimensional Changes (Shrinkage)	AATCC 135-2003

Table 6. (Continued)

Test Category and Description (units)	Test Method
Safety	
Antibacterial Activity Assessment	AATCC 147-1998
Flammability	Standard Test Method for Flammability of Materials Used in Protective Clothing Using a Small-Scale Forced Ignition Test
Electrostatic Clinging of Fabrics: Fabric to Metal Test	AATCC 115-2000
Waste Generation	
Linting: Gelbo Flex Tester with Particle Counter	INDA IST 160.1 (95)
Appearance	
Snagging (subjective rating using photo standard)	ASTM D5362 Bean Bag Method
Pilling (subjective rating using photo standard)	ASTM D4970-02 Martindale Tester
Colorfastness to Perspiration	AATCC 15-1973
Accelerated Washing (subjective evaluation of colorfastness, general wear, & appearance)	AATCC 61-2003

Research Objective: Test candidate materials according to standardized test procedures in order to verify performance characteristics.

Garments were tested according to the standardized test procedures identified in Table 6. A description of each test method by category is found below along with the data that was recorded and the number of specimens that were tested.

Basic Fabric Structure

ASTM D3776: Weight

Weight was measured according to the ASTM D 3776 small swatch option. Three eight inch by eight inch specimens were weighed on an analytical balance and the weight calculated in mass per unit area (oz/sq yd). The average weight was recorded.

KES FB-3 Compression Tester: Thickness

Thickness was measured on the Kawabata (KES)–FB3 compression tester. The thickness of a 2 cm^2 area was measured at 0.5 gf/ cm^2 and reported in millimeters. Three eight inch by eight inch samples were measured and the average was recorded.

Durability

ASTM D 3786-01: Standard Test Method for Hydraulic Bursting Strength of Textile Fabrics—Diaphragm Bursting Strength Tester Method

This test method describes the measurement of the resistance of textile fabrics to bursting using a hydraulic diaphragm bursting tester. Each fabric sample was clamped over an expandable diaphragm. The diaphragm was expanded by fluid pressure to the point of specimen rupture. The total pressure required to rupture the specimen was reported as the bursting strength. A higher bursting strength implies a more durable fabric.

Comfort

ASTM D 1388-96 (Reapproved 2002): Standard Test Method for Stiffness of Fabrics (Cantilever Test Option)

The Cantilever Test measures the stiffness properties of fabrics or its resistance to bending. Bending length was measured and flexural rigidity was calculated. Bending length refers to a measure of the interaction between fabric weight and fabric stiffness as shown by the way in which a fabric bends under its own weight. Flexural rigidity is a measure of stiffness where two equal and opposite forces are acting along parallel lines on either end of a strip of unit width bent into unit curvature in the absence of any tension.

A fabric specimen one inch by eight inches was slid in a direction parallel to its long dimension, until its edge projected from the edge of the horizontal surface of the cantilever bending mechanism. The length of the overhang was then measured when the tip of the specimen was depressed under its own mass at a 41.5° angle with the horizontal. From this measured length, the bending length and flexural rigidity were calculated. The stiffer fabrics will have a higher measurement for bending length and flexural rigidity. Eight samples of each fabric were tested (four in the warp direction and four in the fill direction).

Full Kawabata Evaluation System (KES) Evaluation

The Kawabata Evaluation System (KES) was employed to make an objective measure of the fabric tactile quality. KES includes five instrument tests that measure mechanical and surface properties of fabrics with low forces applied generating a total of 16 different test parameters. The following key measurement was selected from the test series and performed on three samples of each fabric:

Tensile

The tensile test, done on the KES-FB1 Tensile-Shear Tester, measures the stress/strain parameters at the maximum load of 250 gf/cm for standard knits.

Vertical Wicking Test Method

The liquid transport rate was measured according to a vertical strip wicking test. One end of a specimen strip cut one inch wide by 6 inches long was clamped vertically with a dangling end immersed in about three millimeters of distilled water. The height to which the water is transported along the strip was measured at one, five, and ten minute intervals and reported in centimeters. Three lengthwise (wales) and three crosswise (courses) samples of each fabric were tested. The final result is the average of three wicking values.

Q_{max}

This hand property measurement is calculated from measures of thermal transport made with the KES-F7 Thermolabo instrument. It was used to assess the warm/cool sensations of the test samples. The q_{max} value (watts/m^2°C) indicates the instantaneous warm/cool feeling sensed when there is initial contact of a material with the skin surface. A higher value of q_{max} indicates a more rapid movement of heat from the body to the material surface resulting in a cooler feeling fabric. A smoother fabric will create a cooler feeling whereas a rougher fabric will create a warmer feeling. Three specimens of each fabric were tested.

Heat Loss: Sweating Hot Plate Method (min, comf, and max values)

The Kawabata ThermoLabo hot plate system was used to measure the heat transfer properties of the test samples. Heat transfer is the measure of the heat flow from the test plate (heated to a skin surface temperature of 35°C) through the material into the test environment (21°C, 65% RH), and was determined in watts/m^2 °C for dry skin and wet skin conditions. Comfort parameters, calculated from measurements of heat transfer, include:

a. ***Clo*** is a unit of thermal resistance that indicates the insulating ability of the test material. It is derived from measure of dry heat transfer (nonsweating plate). Materials having higher clo values provide wearers with more thermal protection, or insulation. A clo value of 1 represents a typical man's business suit expected to maintain thermal comfort for a person in a normal indoor environment. Requirements vary from about 0.5 clo for summer wear to 4 to 5 clo for outdoor winter clothing.

b. The ***i_m value***, or permeability index, indicates moisture-heat permeability through the material on a scale of 0 (totally impermeable) to 1 (totally permeable). This comfort parameter indicates the effect of evaporating skin moisture on heat loss as in the case of a sweating skin condition.

c. ***Comfort limits***, watts/m^2, are the predicted metabolic activity levels that wearers may sustain and maintain body thermal comfort in the test environment. Three comfort limits will be reported:

- The min is associated with maintaining a dry skin surface
- The comf is associated with having 20% of the skin surface wet with sweat and is considered to be the key comfort limit which more accurately represents typical activity levels of people
- The max level is for a 100% wet skin condition indicating a person is in a highly stressed state

GATS: Liquid Moisture Management

Demand Wettability

The two parameters most commonly used to characterize the properties of absorbent products are the rate of absorbency and the total absorbent capacity. The former determines the rapidity with which fluid is imbibed while the latter determines the total capacity of the material to absorb and hold fluid.

Demand wettability was measured by the amount of water driven from a water filled reservoir. To conduct the test, a special specimen cell and cover were used. The test specimen was positioned on a plate that contains numerous fine pores. This permits the test specimen to contact the entire area, and thus provides a more accurate simulation of a fabric in contact with sweat wetted skin.

A special cover was used to induce transport of fluid through the thickness and evaporation from the surface. The cover has 54, 3-inch long pins uniformly distributed over the area of the test space. These pins act to separate the cover plate from the fabric sample and permit air to circulate over the surface of the test sample. The amount of fluid lost from the reservoir was recorded as a function of test duration.

There is a 2 mm diameter hole at the bottom center of this porous plate that is connected to a fluid reservoir. The level of the cell was adjusted to give zero hydrostatic head. This guarantees that absorbency takes place strictly on demand. A solenoid valve supplies fluid from the fluid reservoir equal to the amount the specimen can absorb. A fluid sensor automatically weighs the amount of water supplied. The reported absorption parameters include:

Q absorbency rate, grams/minute
The rate of fluid absorbency.

Drying Behavior

This test was performed to determine the drying properties (drying rate or time until dry) of saturated fabric. The exact amount of water to add to the fabric was determined by the absorption test in GATS. After the water has saturated the fabric, the weight was recorded, airflow across the plate was set, and timing was started. Weight was recorded after 10-minute intervals and until the samples returned to their approximate original dry weight. Six specimens of each garment were measured and averaged.

Garment Care

AATCC 135-2003: Dimensional Changes in Automatic Home Laundering of Fabrics

This test method determines the dimensional changes in fabric when subjected to automatic laundering procedures commonly used in the home. Before the shirts were laundered, a permanent marker was used to mark a distance of ten inches along the length of the shirt and ten inches along the width. Garments were washed in four pound loads (medium size) using a warm wash and cold rinse. The amount of detergent suggested for a medium sized load was used and the garments were tumble dried on a warm setting. Each garment endured one wash cycle and one drying cycle.

Once the laundering was complete, the distance between the ten inch marks made prior to laundering were recorded. The results of this test procedure show the percent of shrinkage that occurs for the width and length of the garment.

ASTM D 4265-98: Standard Guide for Evaluating Stain Removal Performance in Home Laundering

Stains are artificially applied in a standardized manner to fabric specimens for the stain removal procedure. The stain types chosen for the test were based on analysis of astronaut menus and personal communication with an astronaut. Once each stain was applied to a single piece of fabric (size of stain was roughly two inches in diameter), the stained specimens were placed in a dark room for a minimum of one day. The specimens were then washed, dried and evaluated according to the degree of stain residue left. Each stain was applied once to each sample garment.

Safety

AATCC 147-1998: Antibacterial Activity Assessment of Textile Materials: Parallel Streak Method

The Parallel Streak Method is a relatively quick and easily executed qualitative method to determine antibacterial activity of diffusible antimicrobial agents on textile materials. Specimens of the test material were placed in intimate contact with nutrient agar which had been previously streaked with an inoculum of a test bacterium. After incubation, a clear area of interrupted growth underneath and along the sides of the test material indicates antibacterial activity of the specimen. Because of the high cost of this test procedure, only four garments were chosen for testing (the cotton control, one of the 100% polyester garments, and the two garments that claim to have antibacterial properties).

AATCC 115-2000: Electrostatic Clinging of Fabrics: Fabric-to-Metal Test

This test method evaluates the relative clinging tendency of certain fabrics due to electrostatic charge generation. A metal plate was used to simulate the problems of clinging observed between charged garments and the human body. Time was reported to the nearest minute required for a test specimen to decling from the metal plate. Three warp and three fill specimens were tested.

Standard Test Method for Flammability of Materials Used in Protective Clothing Using a Small-Scale Forced Ignition Test

This standard provides a method of testing the flammability of materials used in protective clothing using forced edge ignition and establishes four classes of flammability based on the rate of flame spread. A dried specimen was inserted in a frame and held in a special apparatus at an angle of 45°. A standardized flame was applied to the lower edge for a sufficient time to ignite the specimen (but no more than 10 seconds), and the time required for the flame to proceed up the material a distance of 127 mm (5 in) was recorded. Notation was made as to whether the base of a raised-surface material ignites, chars, or melts. Four specimens of each garment were tested.

Waste Generation

INDA IST 160.1 (95): Standard Test Method for Resistance to Linting of Nonwoven Fabrics

The INDA method demonstrates the relative propensity of fabrics to generate lint particles when subjected to a continuous flexing and twisting movement. This motion simulates to some extent the type of motion that takes place on a sleeve being bent repeatedly at the elbow. The procedure requires a laminar flow hood, Gelbo Flex unit, flexing chamber, and particle counter.

Flexing was produced by the Gelbo Flex Tester which simultaneously twists and compresses the test fabric. Each specimen runs for five minutes and simulates the lint generated by 300 arm flexes. Air was sampled with a tube leading from the chamber to the particle counter. During the flexing, air was withdrawn from the flexing chamber and examined for particulates using a laser particle counter. The particle counter differentiates the particles by size (0.3, 0.5, 1, 5, and 10 microns). Three specimens of each fabric were tested. Particle counts were recorded and averaged for each specimen at each particle size.

Appearance

ASTM D 5362-97a: Standard Test Method for Snagging Resistance of Fabrics (Bean Bag)

This test method determines the snagging resistance of fabric. Each fabric specimen was made into a cover for a bean bag. Then, the specimen and bean bag unit were tumbled for 100 revolutions in a cylindrical test chamber which is fitted on its inner surface with rows of pins. The degree of fabric snagging was evaluated by comparing the tested specimens with visual rating standards (photographs of snagged fabrics). A total of two bean bags were tested for each fabric, and each side was evaluated from 1 (very severe snagging) to 5 (no snagging).

ASTM D 4970-02: Standard Test Method for Pilling Resistance and Other Related Surface Changes of Textile Fabrics: Martindale Tester

This method determines the resistance to the formation of pills on fabric using the Martindale tester. Fabrics were mounted on the Martindale tester, and the face of the test specimen was rubbed against the face of the same mounted fabric in the form of a geometric figure, which simulates normal wear, for 100 movements. The degree of fabric pilling produced by this action was evaluated by comparing the test specimen to a visual standard (photographs of fabrics showing a range of pilling resistance). The face of each specimen was rated subjectively from 1 (very severe pilling) to 5 (no pilling). Two samples of each fabric were tested.

AATCC 15-1997: Colorfastness to Perspiration

This method is used to determine the fastness of colored textiles to the effects of acid and alkaline perspiration. A specimen was first wet out in simulated acid perspiration and alkaline perspiration (according to AATCC 15-1973). Each test specimen was then placed on a glass plate along with a cotton test fabric and subjected to a fixed mechanical pressure. The specimen was allowed to dry slowly at a slightly elevated temperature (100°F). After conditioning, the specimen was evaluated for color change and the cotton test fabric was evaluated for color transfer. One sample of each fabric was tested.

AATCC 61-2003: Colorfastness to Laundering, Home and Commercial: Accelerated (Test No. 2A)

For Test No. 2A, each specimen was placed inside a stainless steel canister along with AATCC standard detergent, water, and 50 stainless steel balls. The canisters were then locked into a laundering machine called a Launder-Ometer. The Launder-Ometer rotates the closed canisters in a temperature controlled water bath for 45 minutes. The steel balls replicate the abrasive action of five typical machine launderings. A total of eight tests on one specimen of each garment were run in order to simulate 40 typical machine washes.

The weight, thickness, shrinkage, colorfastness, staining and physical appearance of each specimen were evaluated. While appearance was rated subjectively by evaluating the look and feel after washing, staining and colorfastness were evaluated using standard methods.

Staining was evaluated by attaching a strip of multifiber test fabric (containing bands of acetate, cotton, nylon, silk, viscose rayon, and wool) to the specimens and rating the degree of staining based on the AATCC Gray Scale for Staining. The AATCC Gray Scale for Colorfastness was used as a rating guide for the degree of change in colorfastness between the washed and unwashed samples.

Evaluate

Research Objective: Evaluate the performance of each garment as compared to others and recommend the candidate garments that best meet requirements and rate highest on performance and user priorities for IVA use.

Garments were evaluated using Pugh concept selection. The Pugh method is used to evaluate multiple options against each other, in relation to a baseline option. Using the Pugh method, garments were ranked as "better than", "same as", or "worse than" when compared to the control garment. A weighted Pugh was also used for evaluation to assure that those requirements ranked higher in importance received a higher percentage weight to the total score. Garments receiving the highest ranking were recommended for use in IVA applications.

Research Objective: Use the above results and processes to develop a model for NASA to guide in future selection of IVA clothing.

NASA currently has no clearly defined, structured process for choosing IVA garments. The model developed in this study will allow NASA to select IVA clothing for LDSF in a more systematic manner.

CHAPTER IV

RESULTS

Through the previous chapters, the following research objectives have been addressed:

Analyze

1. Collect information on astronaut and environmental needs as well as NASA and related standards and practices (Chapter II).

Define

2. Define the performance requirements for IVA clothing (Chapter II).

Ideate

3. Perform a market survey of COTS materials that could potentially meet requirements and represent the latest in textile innovation (Chapter II).

Select

4. Select candidate garments whose performance claims best match IVA requirements (Chapter III).

Implement

5. Identify the test methods best suited to measure the critical performance categories of each garment (Chapter III).

Now that test methods have been identified and candidate garments have been chosen, the following objectives will be addressed through Chapter IV:

6. Test candidate materials according to standardized test procedures in order to verify performance characteristics.

Evaluate

7. Evaluate the performance of each garment compared to others and recommend the candidate garments that best meet requirements and rate highest on performance and user priorities for IVA use.

8. Use the above results and processes to develop a model for NASA to guide in future selection of IVA clothing.

Each of the ten candidate materials (restated in Table 7) were tested and evaluated following standardized test procedures in order to determine their performance characteristics, as stated in Objective 6. Manufacturer's claims for the garments are found in Table 5 (p. 57). The tables and figures in this chapter demonstrate the test results for each garment in all seven performance categories for evaluation (identified as IVA requirements in Chapter II): Basic Fabric Structure, Durability, Comfort, Garment Care, Safety, Waste Generation, and Appearance.

Table 7. Candidate IVA Garments

Item	Description	Fiber Content
A	Jockey	100% combed cotton
B	Under Armour	100% polyester
C	Nike Dri-Fit	100% polyester
D	Holofiber	92% polyester, 8% Lycra
E	Nomex	100% Nomex IIIA
F	Medalist X-Static	97% polyester, 3% X-Static
G	Domestic Fabrics Wick-A-Way Plus	70% polyester, 30% cotton
H	Wickers Wool	50% Merino wool, 50% FR viscose
I	Land's End Super-T	100% combed cotton
J	Tencel	100% Tencel®

Basic Fabric Structure

Weight

Fabric weight, shown in Figure 4, ranged from less than four to almost ten ounces per square yard. A lower weight garment is preferred for a Mars mission. Lighter and less bulky clothing would reduce weight and logistics costs. The Nike Dri-Fit, Under Armour, and Jockey cotton are among the lightest of these test materials.

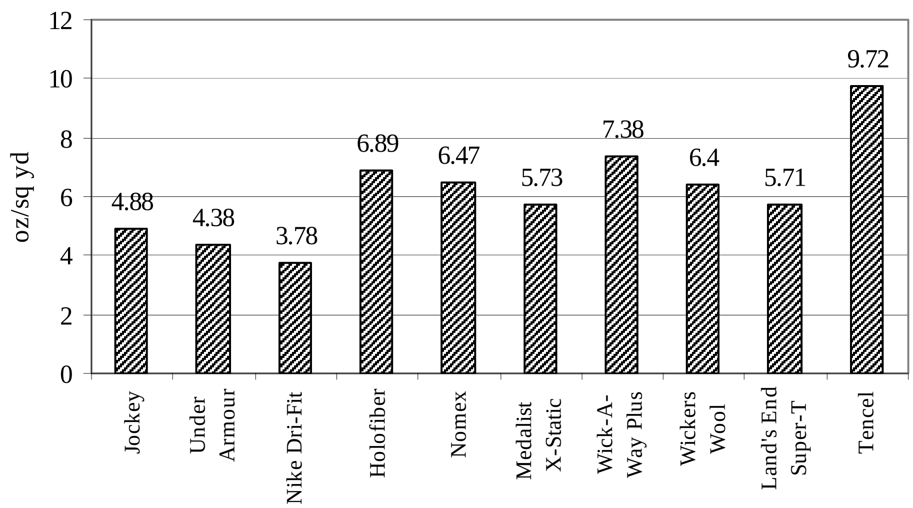

Figure 4. Fabric Weight

Thickness

The thickness of each garment could be an important indicator of IVA clothing performance in several functional categories. Space will be at a premium for the Mars missions. Thinner fabrics, because they are less bulky, could be stored more efficiently. They also tend to hold less water and dry faster, which may be a preliminary indication of their washing and drying performance. The Nike Dri-Fit and Under Armour are the thinnest of all materials tested, and wool is the thickest, as shown in Figure 5.

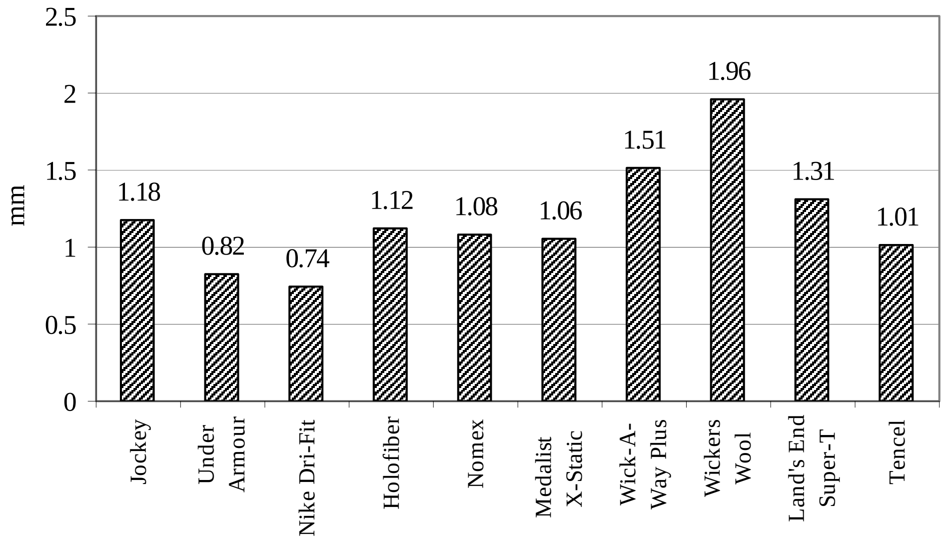

Figure 5. Fabric Thickness

Durability

Bursting Strength

The bursting strength demonstrates the strength and durability of fabrics by measuring the force required to rupture the fabrics. A higher bursting strength implies a more durable fabric. The IVA wardrobe must remain functional for the duration of the mission. Durable fabrics will hold up to frequent washing and wearing and require less frequent replacement. There will most likely be no resupply of clothing materials for a three year, six person Mars mission. A stronger fabric will also be less susceptible to abrasion damage.

All of the garments have an acceptable bursting strength according to standards explored in Chapter II (Table 2). However, as shown in Figure 6, some of the candidate materials possess much greater physical strength and therefore are predicted to outlast the others. For example, the Medalist garment is almost five times stronger than the Wickers wool garment. The Under-Armour, Nike Dri-Fit, Nomex, and Medalist X-Static garments had high measurements for bursting strength, while the cotton and other garment fabrics are significantly lower than these.

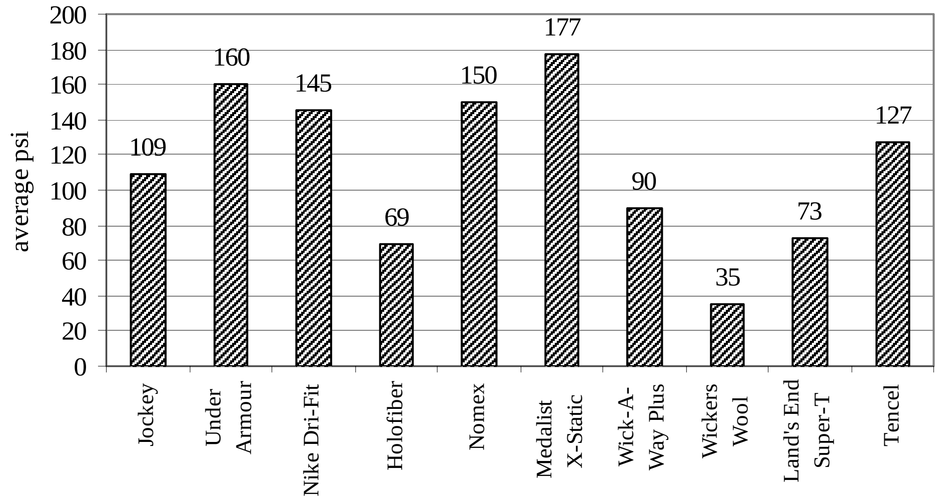

Figure 6. Bursting Strength

Comfort

Clothing comfort is a complex body sensation that is affected by many stimuli. Results of several tests are used in evaluating garment comfort including flexibility, stretch, hand, breathability, and moisture management (wicking, absorbency, and drying time).

Flexural Rigidity

Flexural rigidity measures the stiffness of fabric indicative of the fabric handle or drape. A higher number indicates a stiffer fabric, which could affect comfort and freedom of movement. Fabrics should be flexible enough to provide astronauts with comfort and freedom of movement about the shuttle. The two cotton T-shirts and the Medalist X-Static materials are the stiffest of this test group, and Tencel, Nike Dri-Fit and wool are the most flexible, as shown in Figure 7.

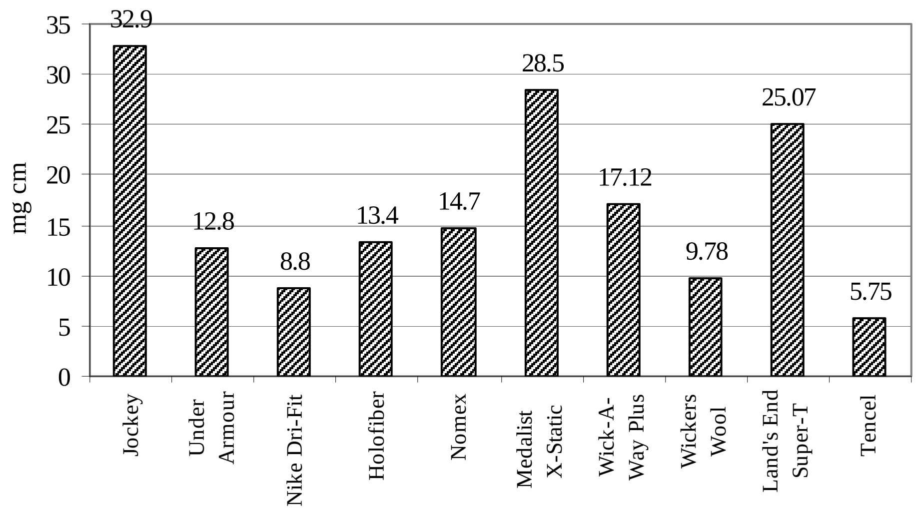

Figure 7. Flexural Rigidity

Tensile Extensibility

The Kawabata Evaluation System (KES) was employed to make an objective measure of the fabric tactile quality. The KES tensile extensibility parameter determines the percent extensibility, or stretch, where higher values indicate a more stretchable fabric material (100% = completely elastic, 0% = completely inelastic). Fabrics with more stretch provide ease in movement. Extensibility can be an important attribute in IVA clothing, where fabrics that stretch with body movement are valued. The results (Figure 8) show that most of these knit constructions are similar in tensile extensibility. However, the Holofiber t-shirt is especially stretchable, at least twice that of the other shirts, because it contains an elastomeric fiber (Lycra).

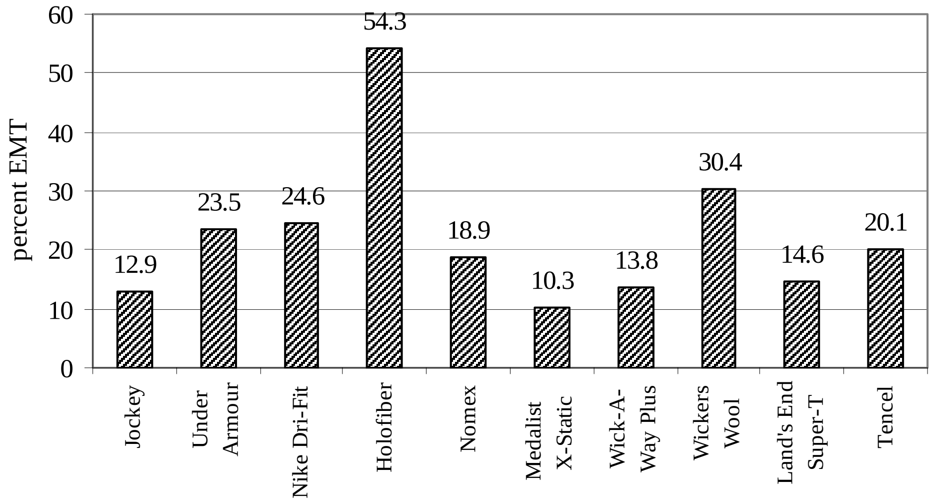

Figure 8. Tensile Extensibility

Q_{max}

This hand property measurement is used to assess the instantaneous warm/cool feeling sensed when there is initial contact of a material with the skin surface. A higher q_{max} value is preferred because it indicates more rapid movement of heat from the body to the material surface resulting in a cooler feeling fabric. A smoother fabric that allows greater contact area of skin and fabric surface creates a cooler feeling whereas a rougher fabric, with less contact area, will create a warmer feeling.

Smooth fabric is preferred to rough fabric for comfort. As the NASA Standard 3000 states, “inner surface of garments shall be free of items which can impede free movement, scratch or chafe the wearer” (NASA, 1995). Tencel, a fabric known for its soft, luxurious hand, displayed the highest Q_{max} value (Figure 9). The remaining garments performed similarly in this category with the Medalist garment having the lowest q_{max} of the group. This is attributed to the uneven surface of the knit structure.

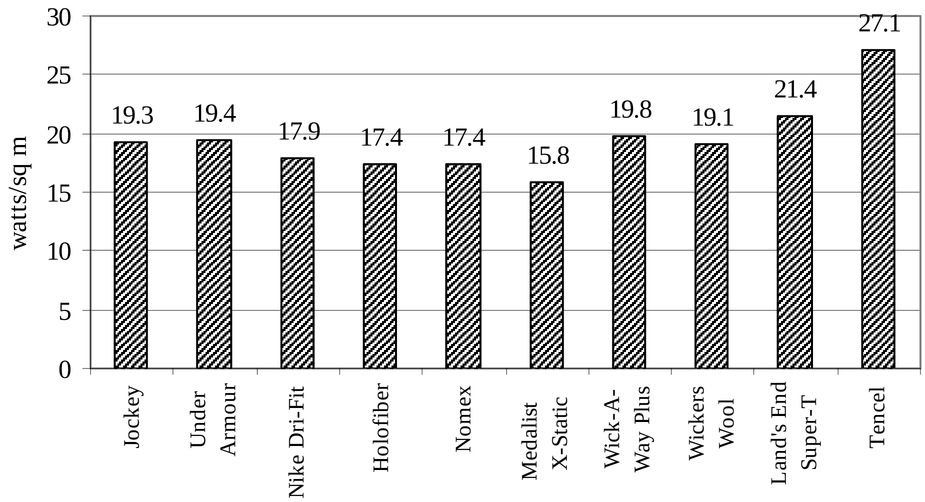

Figure 9. Q_{max} Value

Heat Loss

The Thermal Comfort Index measures the ability of fabric to transmit heat from a warm simulated sweating skin surface to a cooler ambient environment, known as the breathability of clothing materials. The Thermal Comfort Index value for each shirt represents the predicted work level, in metabolic rate, with higher values denoting that a more vigorous level of work is attained before the wearer experiences thermal discomfort. Therefore, higher values of this index indicate materials that are more able to transmit body heat and evaporative thermal energy as insensible perspiration. A breathable fabric promotes comfort by allowing air to pass through the garment and is preferred for IVA clothing to keep the astronauts feeling dry and cool.

Comparison of the test materials on the basis of this index shows that all these knit materials are relatively open structures that possess good predicted ability to transport body heat. The thinner fabric materials (Nike Dri-Fit, Under Armour, Tencel and Jockey 100%

cotton samples) seem to have a slight advantage in thermal comfort over the rest of the materials, as shown in Figure 10.

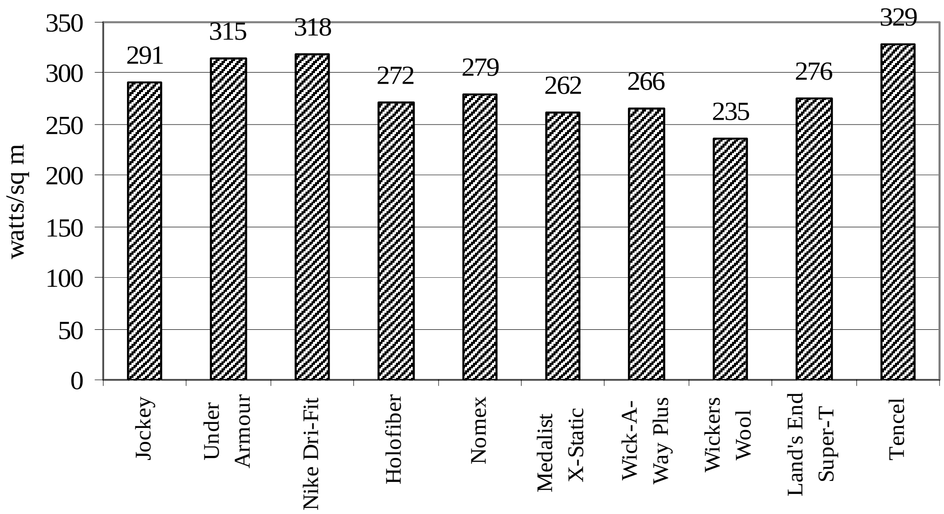

Figure 10. Thermal Comfort Index

Moisture Management

It is important to keep the astronaut's body dry while working in micro-gravity space travel. Fabrics that provide good moisture management properties are recommended. Fabrics should be selected that provide good wickability and vapor transfer. Two different comfort tests were used to measure liquid moisture transfer: vertical wicking and GATS.

Vertical Wicking

The vertical wicking measurement is a prediction of sensorial comfort in wear situations where human activity produces sweating. Higher values indicate fabrics that are more effective in transporting sweat, thereby keeping the skin drier and less susceptible to tactile sensations associated with dampness or clamminess. Astronauts sweat frequently while in space and for health reasons, must spend a lot of time exercising. Unfortunately, in the micro-gravity environment, sweat does not readily evaporate from the skin. A garment that wicks fast should facilitate comfort by keeping the body dry. It should be noted that all the synthetic fiber fabrics out perform the 100% cotton materials in this index of comfort. The Under Armour and Nike Dri-Fit, the high performance polyester fabrics, performed especially well in this comparison, while the natural fiber fabrics appear to be the least wickable, as shown in Figure 11.

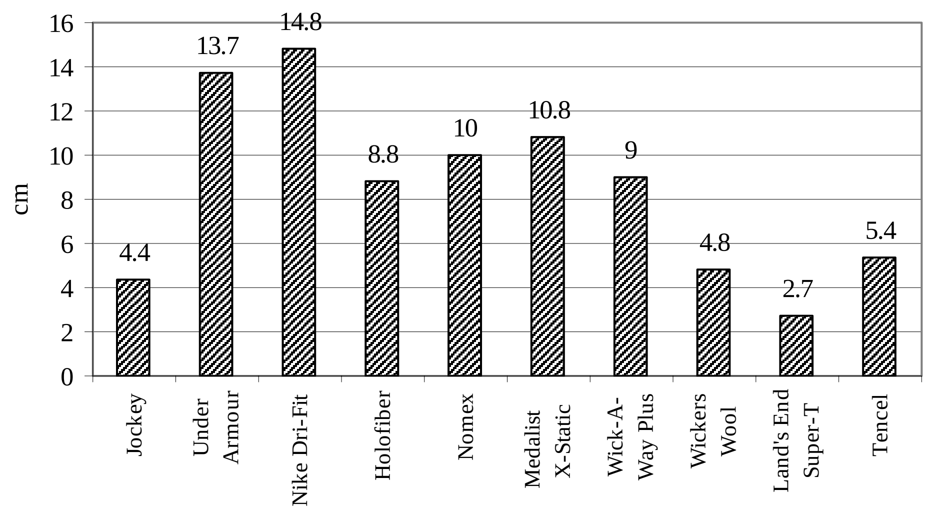

Figure 11. Vertical Wicking

GATS Absorption and Drying Tests: Demand Wettability and Drying Behavior

The Gravimetric Absorbency Testing System (GATS) offers the ability to accurately profile the absorbency and drying behavior of fabrics in a wear configuration simulation. It measures the demand wettability of test fabrics, and therefore simulates lateral wicking of liquid moisture from direct contact with sweating skin. The drying behavior test is performed to determine the drying properties (time until dry) of saturated fabric. Because astronauts sweat frequently, a garment that can absorb more water and dry faster would be preferred. These results can also have some implications for laundering. If garments are to be laundered on board the shuttle, garments that dry faster would reduce the energy needed for laundering.

The absorbency rate and drying time for each garment are reported in Figures 12 and 13. The results show that these garment materials will perform differently in absorption associated wear comfort properties. The two high performance polyester athletic garments (Under Armour and Dri-Fit) had the highest absorption rate and also dried faster than the other garments after being saturated with water. During wear, wicking enhanced synthetic fabrics move liquid sweat from the body, but do not become wet feeling. Cotton fabrics do become wet from sweat absorption, producing wearer discomfort. From the results, we can also conclude that synthetic fiber fabrics would have shorter wash cycles at lower temperatures and dry much faster than cotton fabrics. Consequently, these fabrics would require less energy consumption for care.

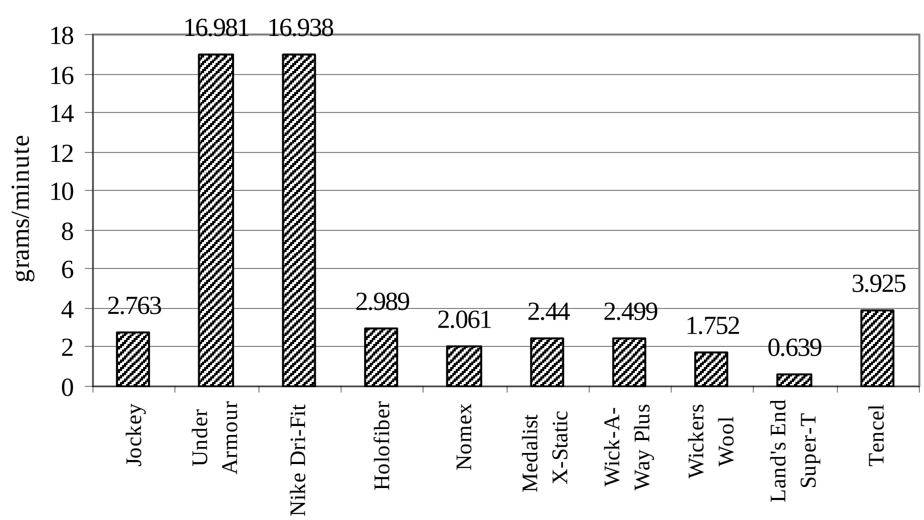

Figure 12. Rate of Fluid Absorbency

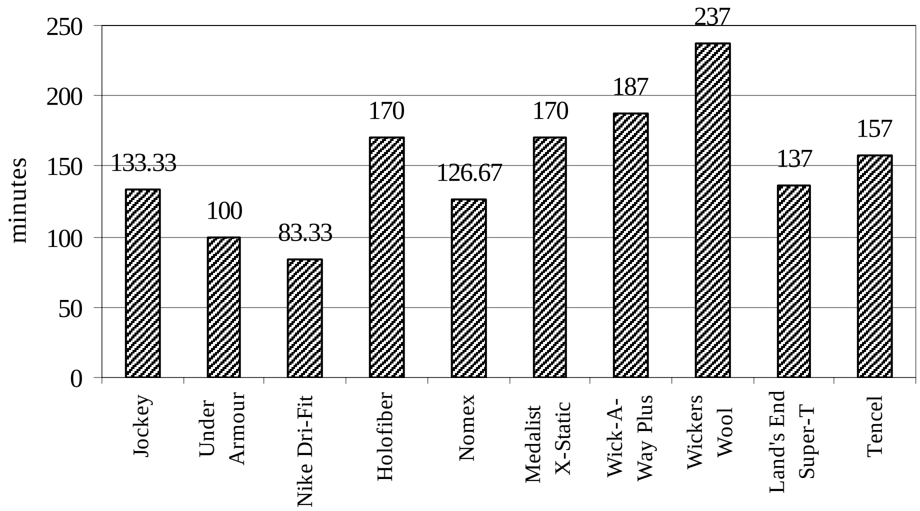

Figure 13. Drying Time

Garment Care

Clothing care is a critical consideration in selection of IVA clothing for long duration space flight. Mission payload restrictions are expected to mandate the cleaning and reuse of clothing rather than single wear disposable garments. Clothing selection should be made based on the assumption that the clothes will be cleaned. Therefore, stain resistance and shrinkage are important factors to consider. Fabrics should be selected that minimize efforts required for cleaning and care of the clothing.

Standard Guide for Evaluating Stain Removal in Home Laundering

The stain removal test evaluates the stain removal performance of garments. IVA garments should be resistant to stains or promote easy stain removal in order to minimize efforts required for cleaning and care and to maintain the aesthetic appeal of the garment over the duration of the mission. Stain types were chosen for the Stain Removal test based on analysis of astronaut menus and recommendations from an astronaut contact. The 12 stain types chosen include: coffee, tea, fruit punch, ketchup, mustard, soil, pen ink, liquid makeup, gravy, chocolate milk, mayonnaise, and mineral oil.

Specimens were visually evaluated according to the degree of stain residue left behind after washing using the standard AATCC Stain Release Replica. A rating of five on the AATCC scale indicates no residue stain while a rating of one indicates a significant amount of the stain residue still remains on the fabric. Table 8 displays the residue rating results for each garment.

When stain ratings are averaged for all stain agents, as shown in Figure 14, most of the garments performed similarly. However, the detailed results show there are staining problems for some specific fabric-agent combinations. The two cotton t-shirts and Tencel shirt retained more stain residues and were rated unacceptable in more cases than synthetic fiber fabrics. Seven of the twelve stains left behind a residue on the cotton t-shirts while the rest of the garments showed residue from less than five stains. Ball point pen ink was the most difficult to remove. Seven of ten samples rated three or lower in this category.

Table 8. Stain Ratings for Stain Removal Test

Item	Coffee	Tea	Fruit Punch	Ketchup	Mustard	Soil	Pen Ink	Liquid Makeup	Gravy	Choc Milk	Mayo	Mineral Oil
A	5	4	5	5	1	4	3	3	4	5	4	5
B	5	5	5	5	5	5	1	5	5	5	5	5
C	5	5	5	5	5	5	1	5	5	5	5	5
D	5	5	5	5	5	5	5	5	5	5	5	5
E	5	5	5	5	5	5	1	5	4	3	4	5
F	5	5	5	5	5	5	2	5	4	5	5	5
G	5	5	5	5	4	5	3	5	5	5	5	5
H	5	5	5	3	5	5	5	5	5	5	5	2
I	5	4	4	5	3	5	4	4	5	5	4	1
J	5	5	5	5	3	5	3	5	3	5	3	3

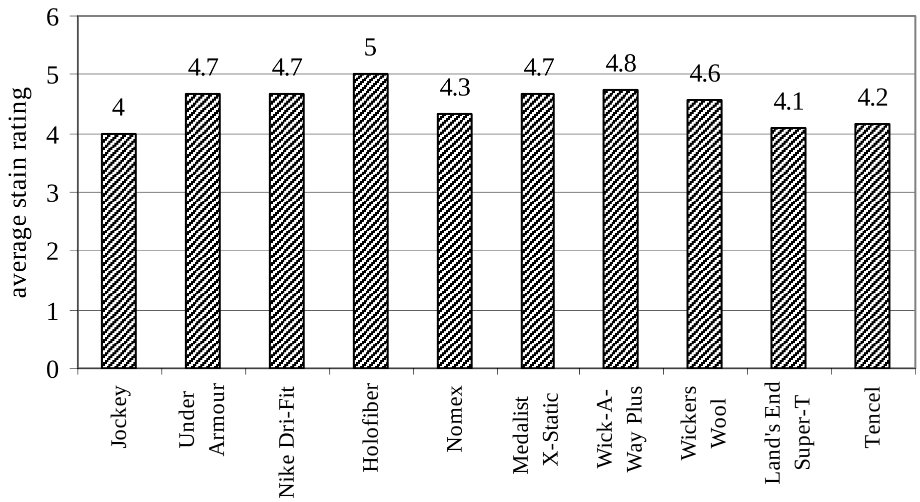

Figure 14. Average Rating for Stain Removal in Washing

Dimensional Changes

The percent of shrinkage that occurred for the width and length of each garment is shown in Table 9. Garments are to be washed and dried on the Mars missions, making shrinkage an important issue to consider. Garments should not demonstrate significant shrinkage. They must provide a consistent fit for the wearer and accommodate changes in weight, height, posture, and body shape that may occur to some extent in weightlessness. Most of the garments shrank five percent or less, which is equivalent to less than half an inch. Standards for comparable applications allow 3% shrinkage (see Table 2). The Jockey cotton garment shrunk significantly more in length than the others, shrinking over an inch lengthwise. The Land’s End cotton t-shirt arrived preshrunk.

Table 9. Percent Shrinkage

Item	Description	Fiber Content	Percent Shrinkage	
			Length	Width
A	Jockey	100% combed cotton	8.1%	3.8%
B	Under Armour	100% polyester	5.0%	2.5%
C	Nike Dri-Fit	100% polyester	2.5%	2.5%
D	Holofiber	92% polyester, 8% Lycra	3.8%	0%
E	Nomex	100% Nomex IIIA	1.3%	1.3%
F	Medalist	97% polyester, 3% X-Static	5.0%	2.5%
G	Domestic Fabrics Wick-A-Way Plus	70% polyester, 30% cotton	5.0%	0%
H	Wickers Wool	50% Merino wool, 50% FR viscose	5.0%	0%
I	Land's End	100% combed cotton	0%	1.3%
J	Tencel	100% Tencel®	5.0%	0%

Safety

IVA clothing should provide safety and protection. In the oxygen-rich environment, fire protection is a consideration. Antistatic clothing will reduce the risk of sparks and ignitions resulting from build up of static charges. Electrostatic charges that may cause fabric to cling to equipment or other surfaces may be deterrent to functionality. Hygiene is also an important safety consideration, especially when garments are worn for days before being changed.

Antibacterial Activity

For antibacterial assessment, common body bacteria of both Gram positive (*Staphyloccus aureus*) and Gram negative (*Klebsiella pneumoniae*) types were tested to determine their ability to grow on each garment. Hygiene is an important safety consideration for the Mars missions. Anti-microbial fabrics that retard microbial growth and prevent odor are desirable. Bacterial prevention is important, especially when garments are worn for days before being changed.

Four of the selected candidate shirt fabrics were tested for antibacterial activity using the parallel streak method, a zone of inhibition test. The control cotton t-shirt, a high performance polyester athletic shirt, the Medalist shirt containing the X-Static silver component, for its antibacterial property, and the Wick-A-Way shirt knitted with antimicrobial yarns were selected for testing. The fabrics were rated according to the following criteria: NZ = No clear zone (specimen does not resist bacteria), NI = No inhibition of bacteria growth under the sample, I = Inhibition of growth under the sample, and mm = Zone of inhibition reported in millimeters.

The results of this procedure, shown in Table 10, indicate that these fabrics will not offer any protection from bacterial growth in the surrounding zone area. The X-Static component in the Medalist shirt and the antimicrobial yarns in the Wick-A-Way shirt had no effect on the growth of organisms in the zone. However, the garments could still be effective on organisms that are being absorbed into the inner structure of the fiber, as in the case of absorption of body perspiration, which the test does not measure.

Table 10. Antibacterial Activity Assessment

Item	Description	Fiber Content	Results (Zone Size)	
			Staphylococcus Aureus	***Klebsiella Pheumoniae***
A	Jockey	100% combed cotton	NZ/NI	NZ/NI
B	Under Armour	100% polyester	NZ/NI	NZ/NI
F	Medalist	97% polyester, 3% X-Static	NZ/NI	NZ/NI
G	Domestic Fabrics Wick-A-Way Plus	70% polyester, 30% cotton	NZ/NI	NZ/NI

Flammability

The test method used to assess flammability determines the ease of ignition of clothing materials and relative ability of the garments to sustain combustion. It measures the rate of flame spread for each garment. The rate of flame spread is indicated by the time required for the flame to proceed up the material, positioned at a 45 degree angle, a distance of 5 inches from the ignition source. A lower flame-spread time indicates a flame that spreads faster when exposed to the garment. The oxygen-rich environment inside the space shuttle creates a potential fire hazard. A higher flame-spread time would be preferred to give the astronauts more time to respond to a fire if one occurred.

Two different burn test results are reported in Table 11: 1) average flame-spread time to the nearest 0.1 second, and 2) burn class according to the following four established classes of burn test results:

Class 1: Normal flammability, relatively slow burning.
Flame-spread time of 20 seconds or more.
Class 2: Normal flammability, moderately flammable.
Flame-spread time of 8 seconds or more but less than 20 seconds.
Class 3: Normal flammability, relatively flammable.
Flame-spread time of 3 seconds or more but less than 8 seconds.
Class 4: Rapid burning.
Flame-spread time of less than 3 seconds.

IBE designates "ignited, but extinguished" and *DNI* indicates the specimen "did not ignite". Eight of the ten samples reported are in the Class 1 burning category. However, the two cotton t-shirts had a shorter average flame spread time of less than 20 seconds, putting them in burn Class 2. It should be noted that, upon exposure to the flame, the Nomex and Wickers Wool fabric (contains FR viscose) either did not ignite (DNI) or ignited but extinguished (IBE). All of the polyester or polyester blend garments performed similarly, with the X-

Static and Nike garments frequently extinguishing before reaching the 5 inch mark. Average flame spread times for each garment are represented in Figure 15.

Table 11. Detail of Flammability Test Results

Item	Description	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Avg	Burn Class
		Flame Spread Time (seconds)							
A	Jockey *(100% combed cotton)*	10.7	11.1	9.8	10.9	12.4	12.4	11.0	2
B	Under Armour *(100% polyester)*	20.2	IBE	23.9	25.2	18.6	22.7	22.0	1
C	Nike Dri-Fit *(100% polyester)*	IBE	22.0	IBE	IBE	IBE	IBE	22.0	1
D	Holofiber *(92% polyester, 8% Lycra)*	24.8	20.2	18.0	21.1	17.9	22.9	20.0	1
E	Nomex *(100% Nomex IIIA)*	IBE	IBE	DNI	DNI	IBE	IBE	N/A	1
F	Medalist *(97% polyester, 3% X-Static)*	25.6	31.2	IBE	IBE	IBE	IBE	28.4	1
G	Domestic Fabrics Wick-A-Way Plus *(70% polyester, 30% cotton)*	26.1	22.4	25.2	22.9	24.2	25.3	24.0	1
H	Wickers Wool *(50% Merino wool, 50% FR viscose)*	IBE	DNI	IBE	DNI	DNI	DNI	N/A	1
I	Land’s End *(100% combed cotton)*	19.0	14.7	14.5	16.4	17.1	15.6	15.7	2
J	Tencel *(100% Tencel)*	21.2	23.5	23.3	24.7	22.9	29.0	23.1	1

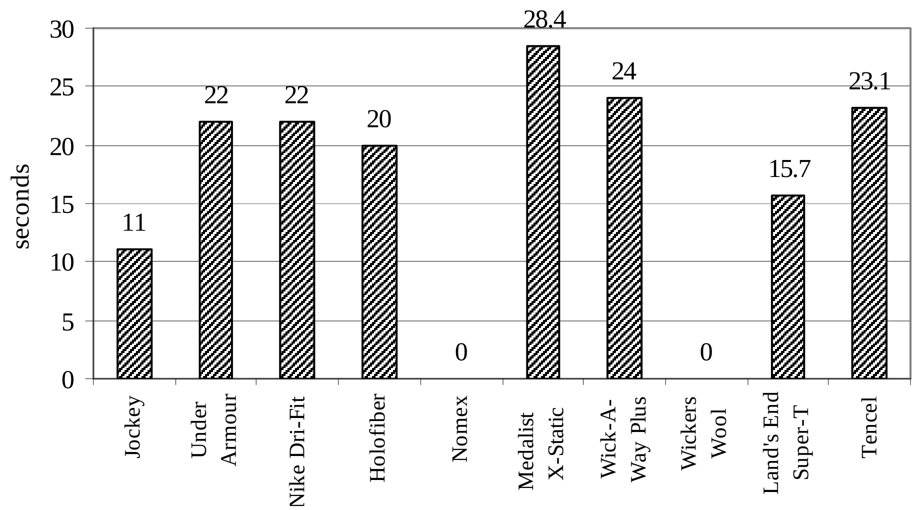

Figure 15. Average Flame Spread Time

Electrostatic Clinging of Fabrics: Fabric to Metal Test

The fabric to metal test evaluates the tendency of certain fabrics to cling due to electrostatic charge generation. Six specimens from each garment were rubbed against standard nylon and polyester rubbing fabrics to create a charged fabric and then clamped onto an angled metal plate. A metal plate is used to simulate the problems of clinging observed between charged garments and the human body. The time is measured for the charge on a fabric specimen to decay to a level where the force attracting the fabric to the metal plate is overbalanced by gravitational forces, therefore causing the specimen to pull away from the plate.

Electrostatic performance is one of the selection criteria mentioned in the NASA Standard 3000 for IVA clothing. Electrostatic charges that cause fabric to cling to equipment or other surfaces may be deterrent to functionality. Antistatic clothing will also reduce the risk of dangerous sparks and ignitions resulting from build up of static charges.

The results, demonstrated in Table 12, show that a majority of the fabrics did not cling to the metal plate, indicating there were no charges created within the fabric from rubbing. The polyester garments (Under Armour, Nike Dri-Fit, Holofiber) had a greater tendency to cling to the metal plate due to electrostatic charge generation, with the Nike Dri-Fit clinging the longest, many times over 10 minutes (the test method states that the test should be discontinued after 10 minutes of clinging). The Medalist garment, also made up largely of polyester, did not cling due to the anti-static property of X-Static.

Table 12. Electrostatic Cling Time

Item	Description	Fiber Content	Nylon Rubbing Fabric (average cling time)	Polyester Rubbing Fabric (average cling time)
A	Jockey	100% combed cotton	No cling	No cling
B	Under Armour	100% polyester	4 minutes	6 minutes
C	Nike Dri-Fit	100% polyester	9 minutes	8 minutes
D	Holofiber	92% polyester, 8% Lycra	5 minutes	5 minutes
E	Nomex	100% Nomex IIIA	No cling	No cling
F	Medalist X-Static	97% polyester, 3% X-Static	No cling	No cling
G	Domestic Fabrics Wick-A-Way Plus	70% polyester, 30% cotton	No cling	No cling
H	Wickers Wool	50% Merino wool, 50% FR viscose	No cling	No cling
I	Land’s End Super-T	100% combed cotton	No cling	No cling
J	Tencel	100% Tencel®	No cling	No cling

Waste Generation

Linting

The linting method evaluates the propensity of clothing fabrics to generate lint particles when subjected to repeated flexing and twisting movements. This motion is produced by a laboratory flexing machine designed to simulate the flexing action that occurs when a sleeve is bent repeatedly at the elbow. A laser particle counter is used to measure the number of particles in the air in the 0.3 to 10 micrometer size range. The higher the particle count, the more lint (waste matter) is produced from bending and flexing. Table 13 shows the number of particles counted at each particle size as well as the total number of particles collected for each garment. Figure 16 displays these results graphically.

Many NASA flights have had problems with airborne particles from clothing. The debris has caused smoke detector problems, blocked air flow, and overheating of avionics equipment. A low linting garment is preferred to prevent these problems from occurring.

These data confirm the relative tendency of cotton clothing materials to generate a greater number of airborne lint particles than materials made from synthetic fibers, such as polyester or Nomex. Of the synthetic materials tested, the Medalist X-Static and Tencel samples generated the most particles. The high amounts of lint produced by these garments can be attributed to the open and loose knit structure of the Medalist garment and the tendency of Tencel fibers to fibrillate.

Table 13. Linting Results

Item	Description	Fiber Content	Particle Count					
			0.3 microns	0.5 microns	1 micron	5 microns	10 microns	Total Count
A	Jockey	100% combed cotton	52,859	43,678	30,830	10,663	848	138,878
B	Under Armour	100% polyester	2,447	2,069	1,639	748	253	7,157
C	Nike Dri-Fit	100% polyester	2,998	2,014	1,493	672	234	7,411
D	Holofiber	92% polyester, 8% Lycra	3,356	2,913	2,352	1,141	287	10,049
E	Nomex	100% Nomex IIIA	5,173	4,150	2,911	1,074	228	13,536
F	Medalist X-Static	97% polyester, 3% X-Static	17,848	15,707	12,333	4,529	1,204	51,621
G	Wick-A-Way Plus	70% polyester, 30% cotton	6,352	5,394	4,507	2,730	1,234	20,217
H	Wickers Wool	50% Merino wool, 50% FR viscose	5,441	4,695	3,992	2,527	962	17,617
I	Land’s End Super-T	100% combed cotton	115,978	99,242	77,342	40,100	7,307	339,969
J	Tencel	100% Tencel	180,000	125,867	76,540	24,166	1,853	408,426

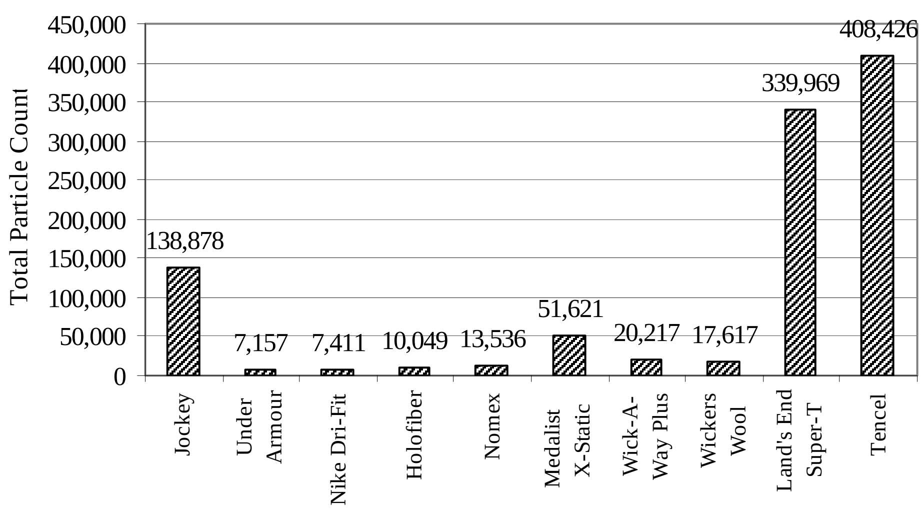

Figure 16. Linting Results

Appearance

Appearance is important for IVA garments that will receive frequent wear and frequent washing. The clothing should resist fading, pilling, snagging, and staining. Aesthetic qualities could impact mood, which is critical in isolation.

Snagging

A snag is a yarn or part of a yarn that is pulled or plucked from the surface of the fabric. A garment that snags often can be a safety hazard on board the shuttle (can catch on protruding devices) and will also lower the aesthetic appeal of the garment over time. The degree of fabric snagging of each test specimen is evaluated visually by comparing it with photographic standards and rating in accordance with the following scale: 5- no or insignificant snagging, 4-slight snagging, 3-moderate snagging, 2-severe snagging, and 1-very severe snagging.

Ratings for the snagging test show that the Under Armour and Nike Dri-Fit fabrics were in the 2-3 rating range, while most of the other fabrics were rated 4.5 to 5.0 indicating they have high resistance to snagging or no snagging. The high strength continuous filament polyester yarns of Under Armour and Nike Dri-Fit fabrics do not easily break when snagged on a sharp object. The object therefore pulls the yarn out of the fabric usually as a protrusion or loop on the surface. Average snag results for each garment are shown in Figure 17.

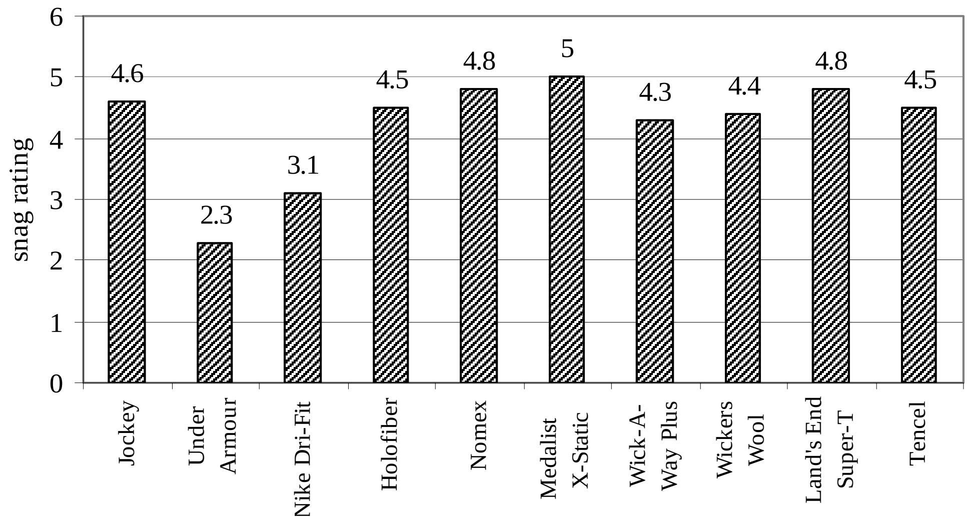

Figure 17. Snagging Results

Pilling

The resistance to the formation of pills on the fabric surface was determined using the Martindale fabric-to-fabric rubbing procedure. The Martindale tester simulates the elbow rubbing against the body while wearing a garment. A garment that pills easily will lower the aesthetic appeal of the garment over time. The test specimens are rated using a visual standard corresponding to the following rating scale: 5-no pilling, 4-slight pilling, 3-moderate pilling, 2-severe pilling, and 1-very severe pilling.

Results of pilling tests are associated with fiber type and yarn form. Fabrics of spun yarns (twisted short fibers) are more susceptible to pilling. The cotton, Holofiber, wool, and Wick-a-Way fabrics did have objectionable pill formation which would affect the aesthetics of the garments over time. Average pilling ratings for each garment are shown in Figure 18.

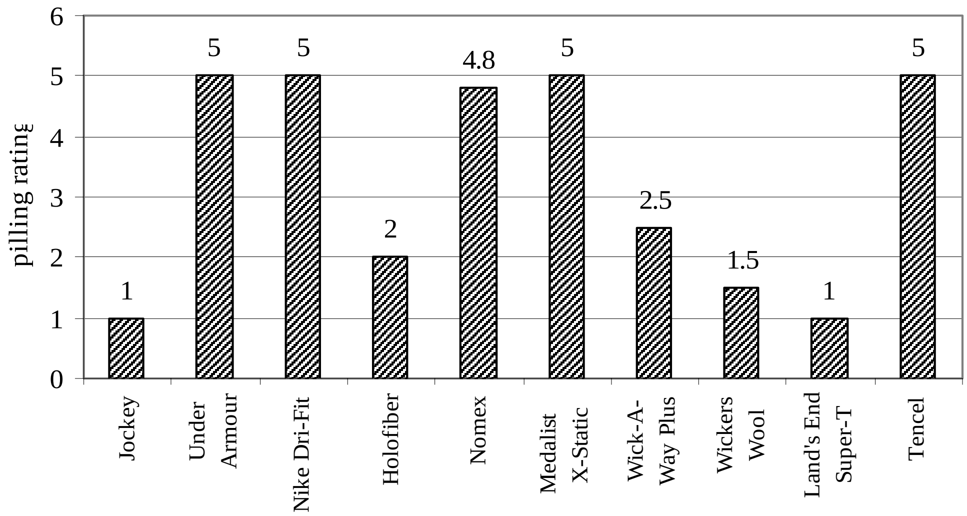

Figure 18. Pilling Results

Colorfastness to Perspiration

This method determines the fastness of colored textiles to the effects of perspiration. Specimens are evaluated for color change and color transfer (staining) after being soaked in simulated acid and alkaline perspiration along with a piece of cotton reference stain fabric. Each fabric specimen is evaluated for color change and the cotton test fabric is evaluated for color staining. Astronauts sweat frequently in space and also endure a strict workout regimen. In order to maintain the aesthetics of IVA clothing, the color of the garment should not fade or stain other fabrics due to sweat.

Staining was evaluated based on the AATCC Gray Scale for Staining. A rating of five indicates negligible or no color transfer (staining) while a rating of one indicates excessive staining. The AATCC Gray Scale for Color Change is used as a rating guide for the degree of fading for each sample. A rating of five on the Gray Scale for Color Change indicates negligible or no change in visual appearance of the color of the fabric, while a rating of one indicates excessive color loss. The results show that neither type of sweat had an adverse effect on the color of the garments or caused excessive staining on cotton fabrics.

Table 14. Colorfastness to Perspiration

Item	Description	Acid Solution		Alkaline Solution	
		Colorfastness Rating	**Staining Rating**	**Colorfastness Rating**	**Staining Rating**
A	Jockey *(100% combed cotton)*	5	5	5	5
B	Under Armour *(100% polyester)*	5	5	5	5
C	Nike Dri-Fit *(100% polyester)*	5	5	5	5
D	Holofiber *(92% polyester, 8% Lycra)*	5	5	5	5
E	Nomex *(100% Nomex IIIA)*	5	5	5	5
F	Medalist *(97% polyester, 3% X-Static)*	5	5	5	5
G	Domestic Fabrics Wick-A-Way Plus *(70% polyester, 30% cotton)*	5	5	5	5
H	Wickers Wool *(50% Merino wool, 50% FR viscose)*	4	4.5	5	4.5
I	Land's End *(100% combed cotton)*	5	5	5	5
J	Tencel *(100% Tencel)®*	4	5	5	4

Accelerated Washing

The accelerated washing test determines the effects of 40 washings on each garment as indicated by measured changes in physical appearance. The goal of this test was to determine if the clothing materials could be expected to retain an acceptable appearance following a regimen of repeated washings that simulate laundering over the course of an extended space mission.

Following the washing protocol, the colorfastness, staining, and physical appearance of each garment material was evaluated. While appearance was rated subjectively by evaluating the look and feel after washing, staining and colorfastness were evaluated using standard rating devices. Staining was evaluated by attaching a strip of multifiber test fabric (containing bands of acetate, cotton, nylon, silk, viscose rayon, and wool) to the specimens and rating the degree of staining for each fabric based on the AATCC Color Transference Scale for Staining. A rating of five indicates negligible or no color transfer (staining) while a rating of one indicates excessive staining.

The AATCC Gray Scale for Colorfastness is used as a rating guide for the degree of color change (fading) between the washed and unwashed samples. A rating of five on the Gray Scale for Colorfastness indicates negligible or no change in visual appearance of the color of the fabric, while a rating of one indicates excessive color loss. Table 15 shows the effects of 40 wash equivalents in a Launder-Ometer on the test fabrics.

Accelerated wash results show that all the candidates for IVA wear, including the cotton t-shirt material, can be expected to withstand 40 repeated washings without unacceptable changes in the physical appearance. All samples retained an acceptable surface appearance and colorfastness. The Medalist (red) and Wickers Wool (blue) fabrics showed slightly higher degrees of staining on certain fabrics.

Table 15. Effect of 40 Simulated Wash Cycles in Launder-Ometer

Item	Description	Fiber Content	Results (after 40 washes)		
			Surface Appearance	Colorfastness Rating	Staining Rating
A	Jockey	100% combed cotton	Smoother feeling and appearance	5	5
B	Under Armour	100% polyester	No change	5	5
C	Nike Dri-Fit	100% polyester	Appears duller than original	4	4.5-5
D	Holofiber	92% polyester, 8% Lycra	Collected a lot of lint from multifiber test fabric	5	4-4.5
E	Nomex	100% Nomex IIIA	Slight dulling from original	4.5	4.5-5
F	Medalist X-Static	97% polyester, 3% X-Static	No change	4.5	acetate 2.5 nylon 3 all others 4.5-5
G	Wick-A-Way Plus	70% polyester, 30% cotton	No change	5	5
H	Wickers Wool	50% Merino wool, 50% FR viscose	Dulling in color, not as bright as original	4	silk 3.5, all others 4.5-5
I	Land's End Super-T	100% combed cotton	No change	5	5
J	Tencel	100% Tencel®	Felt stiffer than original	4	5

Results Summary

A summary of all testing results for the candidate IVA garments is shown in Table 16. These values will be used to evaluate the total package offered by each garment as compared to others in order to determine which garments best fit the needs of IVA apparel. The table includes a “goal” column as a guide to interpreting the results. This column indicates whether the measurement for each attribute should be higher or lower based on IVA requirements. Antibacterial activity assessment is not included in this chart as the results showed that none of the fabrics offer any protection from bacterial growth.

Table 16. Summary of Test Results

PROPERTY	GOAL	Jockey	Under Armour	Nike Dri-Fit	Holofiber	Nomex	Medalist X-Static	Wick-A-Way Plus	Wickers Wool	Land's End Super-T	Tencel
Basic Fabric Structure											
Weight (oz/sq yd)	**low**	4.88	4.38	3.78	6.89	6.47	5.73	7.38	6.40	5.71	9.72
Thickness (mm)	**low**	1.18	0.82	0.74	1.12	1.08	1.06	1.51	1.96	1.31	1.01
Durability											
Bursting (psi)	**high**	109	160	145	69	150	177	90	35	73	127
Comfort											
Flexural Rigidity (mg cm)	**low**	32.9	12.8	8.8	13.4	14.7	28.5	17.12	9.78	25.07	5.75
Tensile Extensibility(%)	**high**	12.9	23.5	24.6	54.3	18.9	10.3	13.8	30.4	14.6	20.1
Q_{max} (watts/sq m)	**high**	19.3	19.4	17.9	17.4	17.4	15.8	19.8	19.1	21.4	27.1
Vertical Wicking (cm)	**high**	4.4	13.7	14.8	8.8	10	10.8	9	4.8	2.7	5.4
Heat Loss (watts/ sq m)	**high**	291	315	318	272	279	262	266	235	276	329
GATS											
Absorbency Rate (g/m)	**high**	2.763	16.981	16.938	2.989	2.061	2.44	2.499	1.752	0.639	3.925
Drying Time (m)	**low**	133.33	100	83.33	170	126.67	170	187	237	137	157
Garment Care											
Shrinkage											
Length (%)	**low**	8.1	5.0	2.5	3.8	1.3	5.0	5.0	5.0	0	5.0
Width (%)	**low**	3.8	2.5	2.5	0	1.3	2.5	0	0	1.3	0
Stain Removal (avg)	**5**	4	4.7	4.7	5	4.3	4.7	4.8	4.6	4.2	4.2
Safety											
Flame Spread Time (s)	**high or N/A**	11	22	22	20	N/A	28.4	24	N/A	15.7	23.1
Static Cling (min)	**low**	0	5	8.5	5	0	0	0	0	0	0
Waste Generation											
Linting (in thousands)	**low**	138.9	7.2	7.4	10.0	13.5	51.6	20.2	17.6	340	408.4
Appearance											
Snagging	**5**	4.6	2.3	3.1	4.5	4.8	5.0	4.3	4.4	4.8	4.5
Pilling	**5**	1.0	5.0	5.0	2.0	4.8	5.0	2.5	1.5	1.0	5.0
Colorfastness to Perspiration											
Acid Solution											
Colorfastness	**5**	5	5	5	5	5	5	5	4	5	4
Staining	**5**	5	5	5	5	5	5	5	4.5	5	5
Alkaline Solution											
Colorfastness	**5**	5	5	5	5	5	5	5	5	5	5
Staining	**5**	5	5	5	5	5	5	5	4.5	5	4
Accelerated Washing											
Colorfastness	**5**	5	5	4	5	4.5	4.5	5	4	5	4
Staining	**5**	5	5	4.5-5	4-4.5	4.5-5	2.5-5	5	3.5-5	5	5

Garment Evaluation

In the final stage of Watkins' development process for functional apparel, garment concepts are evaluated in relation to the design objectives. Watkins states that this process is best accomplished through a ranking and weighting procedure. Ranking criteria involves listing them by how well they satisfy a need and weighting involves assigning a relative importance value to them. Watkins (1995) recommends using a decision matrix, such as the Pugh method, in order to select and rank concepts based on customer needs and client priorities. Pugh Concept Selection (1990) will be used to evaluate the performance of each garment compared to others and recommend the candidate garments that best meet requirements and rate highest on performance and user priorities for IVA use, as stated in Objective 7.

Pugh Concept Selection

Each garment represents a different concept that will be screened using Pugh Concept Selection (1990). The purpose of Pugh Concept Selection (1990) is to narrow the number of concepts in order to choose a targeted concept that satisfies the selection criteria (Weight, Thickness, Durability, Comfort, Garment Care, Safety, Waste Generation, and Appearance). The garment selection method consists of two stages. The first is called concept screening and the second is called concept scoring. Each is supported by a decision matrix which is used to help select the best concept. The concept screening matrix is used if all criteria (or product attributes) are considered equally important, and the concept scoring matrix is used if certain criteria are considered more important than others.

Concept Screening Matrix

The concept screening matrix is used to rate each concept against the control garment, the 100% cotton t-shirt, which represents the current IVA t-shirt. The selection criteria (Basic Fabric Structure, Durability, Comfort, Garment Care, Safety, Waste Generation, and Appearance) are listed along the left-hand side of the screening matrix with the concepts listed at the top. A relative score of “better than” (+), “same as” (0), or “worse than” (-), is placed in each cell of the matrix to represent how each concept rates in comparison to the control garment. The control garment maintains a score of zero. For example, a lightweight garment is preferred for LDSF to Mars. Therefore, the Under Armour and Nike Dri-Fit garments receive a “+” because they are the only garments lighter than the baseline cotton garment. A final score is recorded for each garment by adding up the pluses and minuses, and the garments are ranked based on these scores.

In the concept screening method, each criterion is given equal weight. Therefore, the rankings will give an indication of which garments are overall best suited for IVA apparel, based on their performance on each test, assuming all the criteria are of equal importance. The rankings for each concept are displayed in Table 17.

Table 17. Pugh Concept Screening Matrix

SELECTION CRITERIA	CONCEPTS									
	Jockey (Control)	**Under Armour**	**Nike Dri-Fit**	**Holofiber**	**Nomex**	**Medalist X-Static**	**Wick-A-Way Plus**	**Wickers Wool**	**Land's End Super-T**	**Tencel**
Weight	0	+	+	-	-	-	-	-	-	-
Thickness	0	+	+	+	+	+	-	-	-	+
Shrinkage	0	+	+	+	+	+	+	+	+	+
Durability	0	+	+	-	+	+	-	-	-	+
Stain removal	0	+	+	+	+	+	+	+	+	+
Flammability	0	+	+	+	+	+	+	+	+	+
Electrostatic performance	0	-	-	-	0	0	0	0	0	0
Antibacterial Activity	0	0	0	0	0	0	0	0	0	0
Linting	0	+	+	+	+	+	+	+	-	-
Snagging	0	-	-	-	+	+	-	-	+	-
Pilling	0	+	+	+	+	+	+	+	0	+
Colorfastness/Staining due to multiple washing	0	0	-	-	-	-	0	-	0	-
Colorfastness/Staining due to perspiration	0	0	0	0	0	0	0	-	0	-
Flexibility	0	+	+	+	+	+	+	+	+	+
Stretch	0	+	+	+	+	-	+	+	+	+
Hand	0	+	-	-	-	-	+	-	+	+
Wicking	0	+	+	+	+	+	+	+	-	+
Breathability	0	+	+	-	-	-	-	-	-	+
Drying time	0	+	+	-	+	-	-	-	-	-
Absorbency	0	+	+	+	-	-	-	-	-	+
SCORE	0	13	10	2	7	3	2	-2	-1	6
RANK	7	1	2	6	3	5	6	9	8	4

*Relative scores of +, 0, and - are assigned objectively based on test results shown in Table 16 (p. 103). The pluses and minuses are then added up and the garment with the highest score ranks first (best) while the garment with the lowest score ranks last (worst).

+ Better than the control garment
0 Same as the control garment
- Worse than the control garment

The following rankings and scores were obtained from the screening matrix (from best to worst):

1. Under Armour (13)
2. Nike Dri-Fit (10)
3. Nomex (7)
4. Tencel (6)
5. Medalist X-Static (3)
6. Wick-A-Way Plus and Holofiber (2)
7. Jockey (0)
8. Land's End Super-T (-1)
9. Wickers Wool (-2)

Assuming all the criteria is of equal importance, the Under Armour garment is best suited for LDSF IVA apparel, while the Wickers Wool would be the least suited. The Under Armour garment beat the cotton on performance in 15 out of the 20 categories, and therefore better meets more IVA needs than any of the other garment options. The control garment (Jockey Cotton) ended up ranking seventh in the list, with the other cotton garment ranking even lower. Seven of the garments tested would be a better overall fit than the IVA garment the astronauts currently wear, representing a higher level of performance based on the needs of the user.

The high performance 100% polyester athletic garments performed best overall, with the polyester blends performing in the middle range. The Nomex garment performed surprisingly well on a variety of tests, resulting in a third place ranking. NASA has tended to avoid flame-resistant materials due to their perceptions about its lack of comfort. However, the Nomex performed better than cotton on four out of the seven comfort measurements. While the Tencel garment ranked high, its heavy weight and high linting make it a questionable choice for IVA apparel. Before accepting the rankings as final, the garments should be looked at individually to determine if the results from any of the criteria are unacceptable.

Concept Scoring Matrix

"At some point in the design process, it is important to prioritize criteria so that the relative importance of each plays a part in the selection of the final design" (Watkins, 1995, 349). While the concept screening matrix ranks the best overall concepts assuming all criteria are of equal importance, Pugh's concept scoring matrix uses a weighted sum to determine concept rankings.

The concept scoring matrix assures that those requirements ranked higher in importance receive a higher percentage weight to the total score (Ulrich & Eppinger, 2003). The matrix focuses on more refined comparisons by allowing the user to choose the best garment based on the importance of each criterion. For example, although the Tencel garment rated high overall on the screening matrix, if linting were the most important criteria, it would rate very low on the scoring matrix. The scoring matrix allows the user to make these tradeoffs.

The concept scoring matrix is set up similar to the screening matrix. The selection criteria are listed on the left hand side with the concepts along the top. However, the matrix also includes a "weight" column. In this column, the relative importance of each criterion is listed as a percentage (out of 100). In the "rating" column, each garment is assigned a score based on its potential to meet the criterion. The higher the score, the better the garment meets that criterion. For example, the Nike Dri-Fit garment is the lightest of all the garments, and since a lighter weight is preferred for the Mars mission, it would receive a score of 10. On the other hand, the Tencel garment was the heaviest of all the garments and therefore would receive a score of 1.

The “weighted score” column is calculated by multiplying the rating by the criteria weight. The total score for each concept is the sum of the weighted scores. Finally, each concept is given a rank corresponding to its total score. The rankings give an indication of which garments are best suited based on the importance of each criteria, as well as the garments that are least suited.

Concept Scoring Scenarios

None of the garments performed best in all performance categories. Therefore, the concept scoring matrix allows the user to make tradeoffs based on which attributes they feel are most important. By inputting the concept scoring matrix into an Excel spreadsheet, the weights can be varied to determine their effect on the garment rankings. Weighting can be complicated by the presence of multiple customers or clients, each of whom has a unique set of priorities. A variety of scoring matrices with different weightings can be created for various market segments with different preferences. Concept scoring scenarios were created from the perspective of the customer (astronaut) and the client (NASA) in order to determine the best garment for each group based on their individual needs and concerns.

Customer

The first concept scoring matrix, shown in Table 18, shows garment rankings based on astronaut needs and concerns. Based on personal communication, it was determined that comfort was really the most important attribute of clothing for the astronauts. They wear the clothing on a daily basis and are directly affected by how comfortable they feel. Comfort can influence both productivity and mood.

Table 18. Concept Scoring Matrix (Customer)

SELECTION CRITERIA	W^a	CONCEPTS																			
		Jockey		Under Armour		Nike Dri-Fit		Holofiber		Nomex		Medalist X-Static		Wick-A-Way Plus		Wickers Wool		Land's End Super-T		Tencel	
		R^b	$W*R^c$	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R
Weight	**5%**	8	0.4	9	0.45	10	0.5	3	0.15	4	0.2	6	0.3	2	0.1	5	0.25	7	0.35	1	0.05
Thickness	**5%**	4	0.2	9	0.45	10	0.5	5	0.25	6	0.3	7	0.35	2	0.1	1	0.05	3	0.15	8	0.4
Shrinkage	**5%**	5	0.25	6	0.3	7	0.35	8	0.4	9	0.45	6	0.3	7	0.35	7	0.35	10	0.5	7	0.35
Durability	**5%**	5	0.25	9	0.45	7	0.35	2	0.1	8	0.4	10	0.5	4	0.2	1	0.05	3	0.15	6	0.3
Stain removal performance	**5%**	4	0.2	8	0.4	8	0.4	10	0.5	6	0.3	8	0.4	9	0.45	7	0.35	5	0.25	5	0.25
Safety	**10%**																				
Flammability	5%	3	0.15	6	0.3	6	0.3	5	0.25	10	0.5	9	0.45	8	0.4	10	0.5	4	0.2	7	0.35
Electrostatic performance	5%	10	0.5	9	0.45	8	0.4	9	0.45	10	0.5	10	0.5	10	0.5	10	0.5	10	0.5	10	0.5
Linting	**5%**	3	0.15	10	0.5	9	0.45	8	0.4	7	0.35	4	0.2	5	0.25	6	0.3	2	0.1	1	0.05
Surface Appearance	**10%**																				
Snagging	3%	8	0.24	2	0.06	3	0.09	7	0.21	9	0.27	10	0.3	4	0.12	5	0.15	9	0.27	6	0.18
Pilling	5%	5	0.25	10	0.5	10	0.5	7	0.35	9	0.45	10	0.5	8	0.4	6	0.3	5	0.25	10	0.5
Colorfastness/Staining due to multiple washing	1%	10	0.1	10	0.1	7	0.07	7	0.07	9	0.09	6	0.06	10	0.1	6	0.06	10	0.1	8	0.08
Colorfastness/Staining due to perspiration	1%	10	0.1	10	0.1	10	0.1	10	0.1	10	0.1	10	0.1	10	0.1	9	0.09	10	0.1	9	0.09
Comfort	**50%**																				
Flexibility	5%	1	0.05	7	0.35	9	0.45	6	0.3	5	0.25	2	0.1	4	0.2	8	0.4	3	0.15	10	0.5
Stretch	5%	2	0.1	7	0.35	8	0.4	10	0.5	5	0.25	1	0.05	3	0.15	9	0.45	4	0.2	6	0.3
Hand	10%	6	0.6	7	0.7	4	0.4	2	0.2	3	0.3	1	0.1	8	0.8	5	0.5	9	0.9	10	1
Wicking	10%	2	0.2	9	0.9	10	1	5	0.5	7	0.7	8	0.8	6	0.6	3	0.3	1	0.1	4	0.4
Breathability	10%	7	0.7	8	0.8	9	0.9	4	0.4	6	0.6	2	0.2	3	0.3	1	0.1	5	0.5	10	1
Drying time	5%	7	0.35	9	0.45	10	0.5	4	0.2	8	0.4	4	0.2	3	0.15	2	0.1	6	0.3	5	0.25
Absorbency	5%	6	0.3	10	0.5	9	0.45	7	0.35	3	0.15	4	0.2	5	0.25	2	0.1	1	0.05	8	0.4
Totals	**100%**		**5.09**		**8.11**		**8.11**		**5.68**		**6.56**		**5.61**		**5.52**		**4.9**		**5.12**		**6.95**

a) Weight- The relative importance of each criterion listed as a percentage; arbitrarily assigned based on input from astronauts. The higher the percentage weight, the more important the criteria.

b) Rating- A score each garment is assigned (from 1 to 10) based on its potential to meet the criterion. The higher the score, the better the garment meets that criterion.

c) Weighted Score- Weight*Rating. The weighted scores are added up to produce a total shown highlighted in yellow. A higher total number indicates a garment that is most suited based on the weighted criterion.

*Note- Antibacterial activity assessment is not included in this chart as the results showed that none of the fabrics offer any protection from bacterial growth.

The weights in Table 18 were arbitrarily assigned to represent what the astronauts might feel are the most important attributes based on communication with an actual astronaut. It gives an example of which garments would best meet the needs of the customer. Comfort was ranked with 50% importance while the rest of the attributes ranked similarly, but much lower. The following rankings and scores were obtained from the scoring matrix in order from best to worst:

1. Under Armour and Nike Dri-Fit (8.11)
2. Tencel (6.95)
3. Nomex (6.56)
4. Holofiber (5.68)
5. Medalist X-Static (5.61)
6. Wick-A-Way Plus (5.52)
7. Land's End Super-T (5.12)
8. Jockey (5.09)
9. Wickers Wool (4.9)

The high performance polyester athletic garments appear at the top of the list once again, with the Tencel and Nomex garments also ranked high. The polyester blends appear in the mid range, with the cotton and wool ranking at the bottom of the list. Based on this analysis, a high performance polyester athletic garment would work best to promote comfort and maintain a level of functionality in all other areas.

Client

The goal of this project, as stated by the client (NASA), is to incorporate new technologies within the life support system that will have a dramatic impact on the reduction of mass and waste and provide increased safety and reliability for long duration space flight (The Boeing Company, 2002). Therefore, the most important attributes for the client are a lightweight, low linting, garment that maintains a higher level of safety and functionality.

Table 19 shows an example of how the concept scoring matrix may be filled out by the client based on their priorities. Weight and linting are the two most important criteria, and therefore receive the highest weight. Safety, comfort, and durability are rated slightly higher, while maintaining low thickness, low shrinkage, high stain removal performance and high surface appearance.

Table 19. Concept Scoring Matrix (Client)

SELECTION CRITERIA	W[a]	CONCEPTS																			
		Jockey		Under Armour		Nike Dri-Fit		Holofiber		Nomex		Medalist X-Static		Wick-A-Way Plus		Wickers Wool		Land's End Super-T		Tencel	
		R[b]	W*R[c]	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R	R	W*R
Weight	**25%**	8	2	9	2.25	10	2.5	3	0.75	4	1	6	1.5	2	0.5	5	1.25	7	1.75	1	0.25
Thickness	**5%**	4	0.2	9	0.45	10	0.5	5	0.25	6	0.3	7	0.35	2	0.1	1	0.05	3	0.15	8	0.4
Shrinkage	**5%**	5	0.25	6	0.3	7	0.35	8	0.4	9	0.45	6	0.3	7	0.35	7	0.35	10	0.5	7	0.35
Durability	**6%**	5	0.3	9	0.54	7	0.42	2	0.12	8	0.48	10	0.6	4	0.24	1	0.06	3	0.18	6	0.36
Stain removal performance	**5%**	4	0.2	8	0.4	8	0.4	10	0.5	6	0.3	8	0.4	9	0.45	7	0.35	5	0.25	5	0.25
Safety	**14%**																				
Flammability	7%	3	0.21	6	0.42	6	0.42	5	0.35	10	0.7	9	0.63	8	0.56	10	0.7	4	0.28	7	0.49
Electrostatic performance	7%	10	0.7	9	0.63	8	0.56	9	0.63	10	0.7	10	0.7	10	0.7	10	0.7	10	0.7	10	0.7
Linting	**25%**	3	0.75	10	2.5	9	2.25	8	2	7	1.75	4	1	5	1.25	6	1.5	2	0.5	1	0.25
Surface Appearance	**5%**																				
Snagging	1%	8	0.08	2	0.02	3	0.03	7	0.07	9	0.09	10	0.1	4	0.04	5	0.05	9	0.09	6	0.06
Pilling	1%	5	0.05	10	0.1	10	0.1	7	0.07	9	0.09	10	0.1	8	0.08	6	0.06	5	0.05	10	0.1
Colorfastness/Staining due to multiple washing	2%	10	0.2	10	0.2	7	0.14	7	0.14	9	0.18	6	0.12	10	0.2	6	0.12	10	0.2	8	0.16
Colorfastness/Staining due to perspiration	1%	10	0.1	10	0.1	10	0.1	10	0.1	10	0.1	10	0.1	10	0.1	9	0.09	10	0.1	9	0.09
Comfort	**10%**																				
Flexibility	1%	1	0.01	7	0.07	9	0.09	6	0.06	5	0.05	2	0.02	4	0.04	8	0.08	3	0.03	10	0.1
Stretch	1%	2	0.02	7	0.07	8	0.08	10	0.1	5	0.05	1	0.01	3	0.03	9	0.09	4	0.04	6	0.06
Hand	1%	6	0.06	7	0.07	4	0.04	2	0.02	3	0.03	1	0.01	8	0.08	5	0.05	9	0.09	10	0.1
Wicking	2%	2	0.04	9	0.18	10	0.2	5	0.1	7	0.14	8	0.16	6	0.12	3	0.06	1	0.02	4	0.08
Breathability	1%	7	0.07	8	0.08	9	0.09	4	0.04	6	0.06	2	0.02	3	0.03	1	0.01	5	0.05	10	0.1
Drying time	2%	7	0.14	9	0.18	10	0.2	4	0.08	8	0.16	4	0.08	3	0.06	2	0.04	6	0.12	5	0.1
Absorbency	2%	6	0.12	10	0.2	9	0.18	7	0.14	3	0.06	4	0.08	5	0.1	2	0.04	1	0.02	8	0.16
Totals	**100%**		**5.5**		**8.76**		**8.65**		**5.92**		**6.69**		**6.28**		**5.03**		**5.65**		**5.12**		**4.16**

a) Weight- The relative importance of each criterion listed as a percentage; arbitrarily assigned based on client objectives. The higher the percentage weight, the more important the criteria.
b) Rating- A score each garment is assigned (from 1 to 10) based on its potential to meet the criterion. The higher the score, the better the garment meets that criterion.
c) Weighted Score- Weight*Rating. The weighted scores are added up to produce a total shown highlighted in yellow. A higher total number indicates a garment that is most suited based on the weighted criterion.
*Note- Antibacterial activity assessment is not included in this chart as the results showed that none of the fabrics offer any protection from bacterial growth.

The following rankings and scores (from best to worst) were obtained from the client scoring matrix and represent the most suited garments based on client weighted criteria:

1. Under Armour (8.76)
2. Nike Dri-Fit (8.65)
3. Nomex (6.69)
4. Medalist X-Static (6.28)
5. Holofiber (5.92)
6. Wickers Wool (5.65)
7. Jockey (5.5)
8. Land's End Super-T (5.12)
9. Wick-A-Way Plus (5.03)
10. Tencel (4.16)

The high performance polyester athletic garments as well as the Nomex garment again rank at the top of the list, consistent with the results from the customer and the overall ranking. Although Tencel ranked second on the customer list due to its high level of comfort, because of the high amount of lint it produces and its heavier weight, it ended up at the bottom of the client list due to preferences for low linting.

Suggested Model

Currently, NASA does not have a systematic approach to choosing IVA clothing for missions. Objective 8 involves developing this approach. Cotton has become the standard material of choice over the years because of its tendency to char rather than melt and because astronauts prefer it for comfort. However, since human spaceflight began, there have been many textile developments for targeted applications, such as athletic apparel and protective clothing, which possess high performance properties that may be used for space clothing applications. Into the future, there will continue to be innovations developed in this area.

The process of choosing IVA garments should follow a systematic approach in order to ensure that mission requirements and astronaut needs are incorporated into the garment choice. The IVA Selection Model, shown in Figure 19, is adapted from Watkins recommended design process for functional apparel, and allows the user to identify and obtain the newest innovations in fibers and fabrics available that can better meet a variety of the astronaut's needs, allowing for increased productivity and improvement in logistics. While the model was used as a guide for this research, it can also be adapted for making decisions for future missions, tasks, or explorations. This model is based on NASA's current strategy of choosing commercially available off-the-shelf clothing. The "Results" column in Figure 14 shows the outputs obtained from this research using the IVA Selection Model.

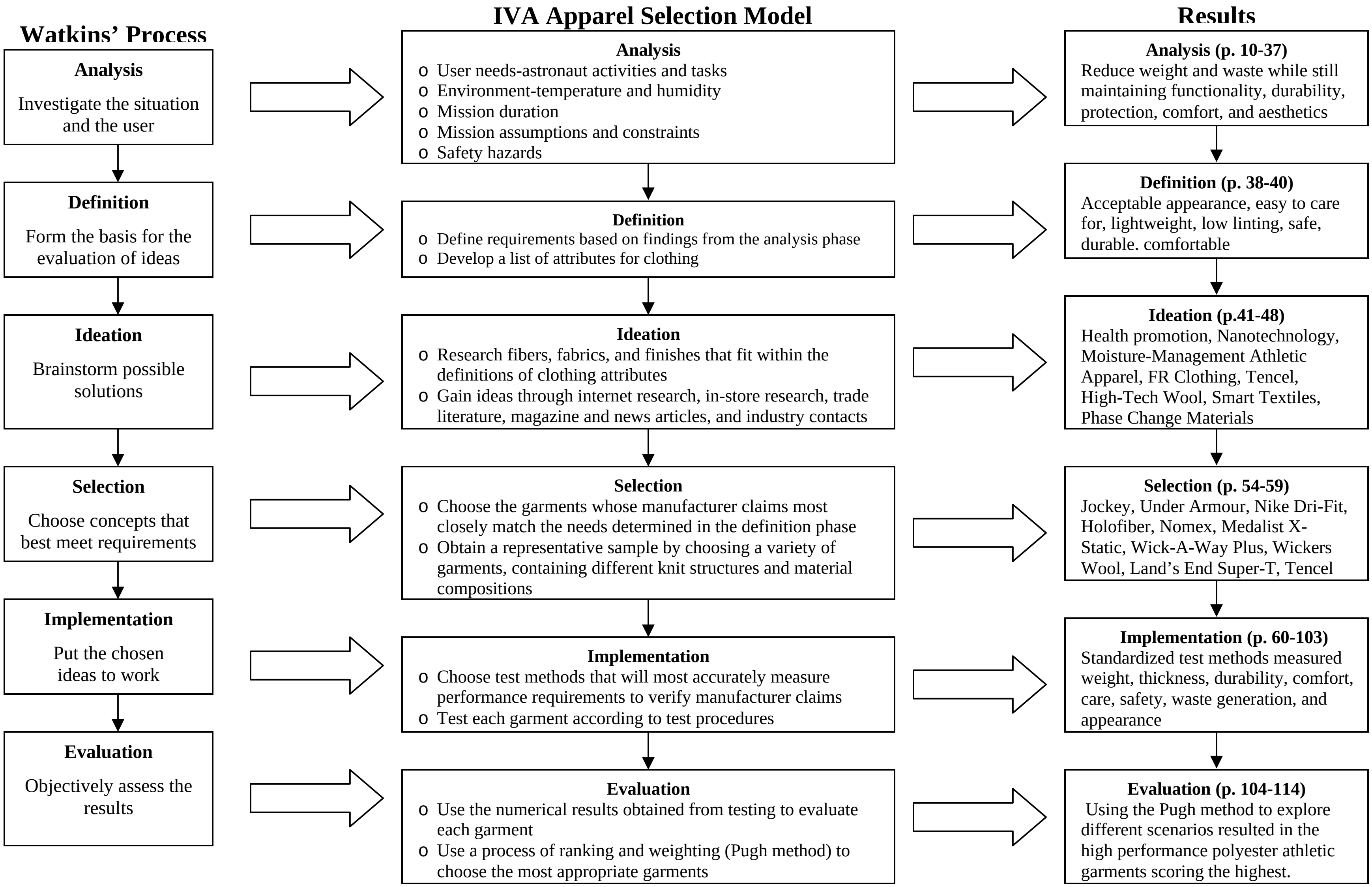

Figure 19. IVA Selection Model

Source: Adapted by L. Fratto based on Watkins, Susan M. (1995). *Clothing: The Portable Environment* (2nd ed.). Ames, IA: Iowa State University Press.

Analysis

The first stage in the model consists of analyzing the situation and the environment in order to determine the needs of the user (also known as the voice of the customer). The researcher should understand issues such as temperature and humidity, the duration of the mission, the mission constraints, astronaut activities and tasks, and environmental and safety hazards. A thorough analysis helps set a clearer definition of the true wearer needs on which the design solutions could be based.

Definition

Definition is a statement of the goals a designer needs to meet to solve a problem. Once the analysis phase has been completed, a list of requirements for the particular mission or task should be developed. The information collected in the analysis phase is sorted through and the most essential elements are determined. A proper definition forms the basis for determining if a particular product satisfies the needs of the user. Requirements, or definitions, should be thought of in terms of apparel attributes (such as durability, comfort, and low linting).

Ideation

The ideation phase uses the definitions determined from the definition phase to brainstorm potential garments that could meet one or all of these requirements. The researcher should survey the market through internet research, newspaper articles, textile magazines, and company contacts to find the latest innovations that could possibly satisfy the mission criteria.

Selection

Once all avenues have been explored in the market survey, the researcher should choose the garments whose manufacturer claims most closely match the needs determined in the definition phase. A variety of garments, containing different knit structures and material compositions, should be chosen in order to get a representative sample. No prior assumptions should be made about how certain materials will perform, but all should be looked at equally and have the same chance of being chosen.

Implementation

Next, the chosen ideas are put to work. Standard test methods should be chosen that appropriately verify the manufacturer claims. Each garment should be tested following the standardized procedures and all results documented.

Evaluation

The numerical results obtained from testing should be used to evaluate each garment. A process of ranking and weighting is recommended to choose the most appropriate garment for the particular mission. Garments can be ranked overall or based on importance weights.

CHAPTER V

SUMMARY, CONCLUSIONS, RECOMMENDATIONS

Summary

The advent of the Mars program has commanded a review of IVA apparel currently used for long duration space flight (LDSF). NASA is seeking innovative ways to reduce the weight impact and linting problems associated with IVA clothing during LDSF while maintaining safety and reliability. The purpose of this study was to evaluate and recommend materials for use in astronaut's IVA wardrobes based on the needs and requirements of LDSF, and to develop a model that would allow NASA to systematically select appropriate IVA clothing.

This research was completed through eight objectives that were based on Susan Watkins' functional apparel design process. Watkins' process provided the necessary inputs in order to produce recommended garments that would improve upon those currently used for LDSF.

First, a thorough examination of clothing and mission needs was conducted and current and historical programs were documented. Based on this analysis, a list of requirements to be applied to clothing for LDSF was developed. A market survey of commercial off-the-shelf (COTS) materials was used to identify and select materials that could potentially meet these requirements. Materials were then tested according to standardized test procedures in order to verify critical performance characteristics and evaluated against the control garment and each other. Finally, a model was recommended to guide NASA in future IVA garment selections.

Conclusions

The current IVA garments are made up largely of cotton, as astronauts prefer it for comfort and NASA prefers a material that would char rather than melt if exposed to fire. Unfortunately, cotton contributes significantly to the weight and waste impacts on the shuttle and is still a flammable material. These impacts will be felt even greater on the long duration of a Mars mission. Many of the materials tested through this research represent an improvement in IVA clothing performance and would reduce these impacts while providing greater safety and reliability.

Garment criteria can be weighted numerous ways using the method presented in this research, producing a variety of results for the best garment choices. A summary of the scenarios explored through this research is found in Table 20. Based on these scenarios, the two high performance polyester athletic garments rank highest overall and on customer and client priorities, making them the best fit for IVA wear. The two cotton garments (the Jockey control and Land's End Super-T) and the Wickers Wool garment scored consistently low on all of the lists. While the Tencel scored high overall and on customer priorities, it scored low on the client list. When situations like this occur, it is usually best to let the client and the customer fill out the criteria weights together (Ulrich & Eppinger, 2003). Table 20 shows that certain fibers or fabrics are more suitable for the requirements of IVA clothing than others.

Table 20. Summary of Garment Rankings

Best - - - - - - Worst	Overall	Customer Priorities	Client Priorities
	Under Armour	Under Armour and Nike Dri-Fit	Under Armour
	Nike Dri-Fit	Tencel	Nike Dri-Fit
	Nomex	Nomex	Nomex
	Tencel	Holofiber	Medalist X-Static
	Medalist X-Static	Medalist X-Static	Holofiber
	Wick-A-Way Plus and Holofiber	Wick-A-Way Plus	Wickers Wool
	Jockey (control)	Land's End Super-T	Jockey (control)
	Land's End Super-T	Jockey (control)	Land's End Super-T
	Wickers Wool	Wickers Wool	Wick-A-Way Plus
			Tencel

Recommendations

According to the method used in this research, the Under Armour garment is the best overall fit for IVA apparel and would provide the greatest improvement over the control garment, with the Nike Dri-Fit not far behind. It is also important to note the presence of Nomex, which consistently ranked high in all three lists. There is some debate about the importance of flame resistant garments in space. However, a NASA report states "internal fires in spacecraft are very rare, but a few events have been serious enough to reinforce the fear of fire hazards in spacecraft operations" (Friedman, Jackson, and Olson, 2000, p. 2). The Nomex garment would be the best choice if NASA wants to keep the lightweight and low linting attributes while providing a safe and comfortable alternative to the current 100% cotton IVA garment.

The structure of Susan Watkins' process for functional apparel development provides all of the necessary tools to successfully integrate needs and requirements into the actual development (or selection) of a suitable garment for a particular task. The use of the adapted process, shown in Figure 19, is recommended as a guide for any future IVA apparel choices that NASA may need to make.

This research provides documentation for redefining clothing standards for LDSF through the testing and evaluation of innovative new textile products. NASA could use the results from the tests performed in this research to define their own testing standards for long duration IVA clothing.

Future Research

Time constraints limited the wardrobe item chosen for testing to a t-shirt. The current IVA wardrobe also consists of sweaters, jackets, pants, undergarments, socks, and athletic shorts. Each of these additional items should be tested in order to determine the most appropriate IVA wardrobe.

The comparison of clothing materials made so far by this research have been found as laboratory tests made on swatches of fabric cut from garments. In addition to the laboratory tests performed through this research, wear tests should also be conducted to assure the measured performance attributes of the fabric translate to the garment level. Garment level attributes such as garment design, style, or fit must be considered for a full and ultimate evaluation. Perhaps certain tests could also be conducted in micro-gravity to see if the performance of each garment would hold up in this environment, since there was no way to take into account the effects of weightlessness during testing.

Testing the universe of innovative textile materials available in the market is beyond the scope of this research. Only ten garments were chosen for testing which is limited in number compared to all the materials available in the market. Also, at the time when spaceflight to Mars actually occurs, roughly twenty years into the future, the textile products available may far exceed the performance of those available today. Therefore, this study should be replicated in the future in order to stay on the cutting edge of textile development. The model presented here will allow NASA to easily replicate this study for any garment type or garment material for any mission.

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