UNIVERSITY OF ALBERTA

DESIGN AND EVALUATION OF THERMAL PROTECTIVE FLIGHTSUITS FOR USE BY CANADIAN FORCES FLIGHT PERSONNEL

BY ©

YI-BIN TAN

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE

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MY FAMI[illegible] CH[illegible]

My grandma Lin [illegible]qiu

My parents Tan [illegible]aoqiang & Zheng Xiaoyun

My anti and uncle Tan Eaci & Wu Zhensheng

My brother and sister Tan Yifeng & Wu Yixin

FOR YOUR UNENDING SUPPORT & LOVE

ABSTRACT

Fire hazard has been one of the most severe dangers faced by military personnel, especially pilots, as a result of the nature of their work. Flightsuits should protect pilots from severe burns in fire accidents and extend their escape time from fire. The flightsuits that Canadian Forces pilots are currently wearing do not provide the thermal protection required by their working environment, and they do not meet all the functional needs of pilots. A great demand for flightsuits that are both protective and comfortable could be seen in the focused group interviews conducted as part of this research.

The purpose of this study was to follow a functional design process in the development and evaluation of thermal protective flightsuits for use by Canadian Forces flight personnel. The framework for the research was adopted from Orlando's (1979) Functional Design Process. This design process allows the designer to follow a strategy-controlled procedure from the general request of the design through to the garment completion and evaluation. It enables the designer to incorporate various design elements into the final design.

The experimental designs incorporated four parameters requested by Defence Research Establishment Ottawa: style, fit, closure system and seam type. With 1-piece and 2-piece styles, close fitting and loose fitting constructions, two closure systems and two seam types (which varied with closure system), a total of eight different flightsuits were designed

using AutoCAD® and PcPattern® programs.

The thermally instrumented mannequin built at The University of Alberta was used to evaluate the thermal protection of the flightsuits. Three replications of each garment style were produced in Nomex® IIIA fabric and tested. The parameters of garment style and closure system had significant effects on the flightsuits' thermal protection. The two-piece flightsuits provided greater protection than the one-piece ones. This result is mainly due to the double layering of garments in the lower torso area.

Cuffed closures on the sleeves and the legs offered greater protection than zippered closures by holding the sleeves and legs in place better, preventing the skin from being exposed to fire due to garment shrinkage and by reducing air movement inside the garment. The stand-up collar provided better protection than the convertible collar, because of its erect shape which fits better around the neck and covers more of the neck than the convertible collar.

Neither front closure type nor seam type had any noticeable effect on the garments' thermal protection. With a low shrinkage fabric in a second round of testing, the loose-fitting garments showed significantly greater protection than the close-fitting ones, demonstrating that the parameter of garment fit can perform an important role in a garment's thermal protection.

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CHAPTER 1

INTRODUCTION

The concept of thermal protection goes back to a time when humans first used animal fur to protect themselves from the cold and later to protect themselves from the heat of fire. Fire hazard has been one of the most severe threats to human beings, because people were in a helpless position without an effective means to protect themselves. In the early seventeenth century, to combat fire hazards chemical flame retardants were first developed for the textile industry. This was a turning point in the textile industry and it enabled people to open up new prospects in the field of thermal protection. Since then chemical flame retardants have been widely applied to materials used in the industry, military and many other fields.

The use of chemical flame retardants started with a treatment for cotton canvas used in Parisian theatres in 1638 and a report on a piece of unburnable cloth from Oxford in 1684. The French king Louis XVIII commissioned Gay-Lussac to find a way of protecting fabrics used in the theatre. In 1820, Gay-Lussac found that ammonium salts of sulphuric, hydrochloric, or phosphoric acid were effective in reducing fabric flammability, a method which remains valid and applicable today (Blum & Ames, 1977). In the 19th century, the British Industrial Revolution exerted a strong impact on the development of protective textiles when the intense heat in industrial working environments required clothing which offered thermal protection. During World War II, the wide range of temperatures encountered by U.S. servicemen prompted the military to undertake extensive research programs to design clothing to protect against temperature extremes. This research by eminent military physiologists was continued into the 1960s and resulted in the development of high temperature resistant fabrics (Veghte, 1982). Related new technologies and scientific research methods have developed considerably since then.

Several synthetic fibres with claimed improvements in thermal stability have been introduced over the past 30 years. In the early 1960's, a new high temperature resistant fabric, DuPont HT-1, was evaluated by both Stoll and Ross (cited in Veghte, 1982a) as a possible material for aviators' flight coveralls. Pioneering efforts in various high-temperature-resistant fabrics and in burn prediction as well as other government sponsored research contributed to the further development of Nomex® (Veghte, 1981). Kevlar® and PBI®, among other high temperature resistant fibres, have been developed and tested. The development of high temperature resistant fabrics has greatly contributed to the development of thermal protective clothing.

In both industry and the military, a high record of accidents involving thermal injury has resulted in an increased concern for safety and requirements for improved working conditions and protection. Statistics indicate that thermal injury is one of the major types of physical trauma in modern society, particularly among firefighters, military personnel such as aircrew members and sailors, and industrial workers such as welders and fuel handlers whose work involves exposure to ignition sources or intense heat. According to Karter's (1980) report on fire fighter injuries in the United States, 95,800 such injuries occurred in the line of duty during 1979. The major cause of those injuries (31.6%) was exposure to fire products. For military personnel, a special concern applies to pilots. Fire associated with aircraft accidents is a major cause of mortality and morbidity in military aircraft operations (Albright, Knox, DuBois, & Keiser, 1971). It results from the unavoidable need for large quantities of highly flammable fuel on board and limited exit facilities (National Materials Advisory Board, 1977). Most fires that aircrew members have to contend with are a result of crashes that involve burning fuel. Combat aircraft crews face an even greater hazard (McLaren, 1985). Therefore, an aviator's flightsuit must protect against the hazardous thermal environment that results from a postcrash fire. A great demand for flightsuits that are both comfortable and protective could be seen in the focused group interviews conducted as part of this research.

Studies of thermal protective clothing for operational military personnel have been conducted since World War II to provide desired protective garments for improved fire safety. Research in this area has involved various aspects of the problem including protective fabrics, principles of heat transfer and skin damage, protective garment design and development of various performance standards and standard test methods.

Much research has been done by commercial, industrial and governmental agencies and research organizations world-wide on the subject of textile flammability and thermal protection. Various laboratory methods have been published by researchers from various countries and research institutes. However, there is no international agreement on how to assess the threat or how to evaluate the capability of clothing to protect the wearer (McLaren, 1985). Recent research in the area has demonstrated that thermal protective performance (TPP) testing, which rates a material's high temperature integrity and thermal insulation, is preferred for small scale fabric tests reflecting occupational exposure conditions. The best way to predict the garment's burning behaviour and protective qualities, however, is using a thermally instrumented mannequin.

Though a significant amount of research on thermal protection has been carried out, most of this research emphasizes thermal protective properties of various fabrics and fabric systems. The fibre content of protective clothing does have a fundamental effect on the flame resistance. The degree of thermal protection offered by a protective garment, however, depends not only on the properties of the particular fibre used but also on a wide range of interrelated factors, including fabric structure, garment design and total garment assembly. Very little work has been done with respect to the functional garment design of thermal protective clothing. In his research on protective clothing design for fire fighters, Veghte (1981) commented that "historically, subjective comments from people exposed to hot temperatures have played the key role in protective clothing design.... The results have been protective clothing with a very wide range of effectiveness" (p. 6). To minimize the design problem, a systematic approach to the design process is required.

STATEMENT OF THE PROBLEM

Previous and current use of thermal protective clothing has been accompanied by problems of discomfort, lack of fit and mobility, and sometimes even poor thermal protection resulting from poor garment design. A particular concern exists regarding flightsuits for pilots, because the nature of their work demands both thermal protection and other functional characteristics. It has been suggested that the lack of a systematic approach to the design process for protective garments is a contributing factor to their poor acceptance (Van Schoor, 1989). Therefore, functional apparel design process, a comprehensive approach that attempts to overcome complex design problems, has become significant in designing protective garments. With a strategy-controlled, functional apparel design process, a designer is able to follow a step-by-step process from the general request for the design through to the garment's completion and evaluation. Doing so allows the designer to incorporate various design specifications into the garment design and therefore meet the physical, social, psychological, and aesthetic needs of potential users.

The purpose of this study was to follow a functional apparel design process in the development and evaluation of flightsuits for use by Canadian Forces flight personnel. The garments were to be evaluated for their thermal protection.

OBJECTIVES

The objectives of this research were as follows:

1. To review reports on previous field accidents and injuries which resulted from poor thermal protection of Armed Forces flight personnel.
2. To collect subjective data from users (Canadian Forces flight personnel) regarding both their needs and the suitability of previous and current flightsuits, through focused group interviews.

3. To employ the functional apparel design process in the development, for Canadian Forces flight personnel, of eight different thermal protective flightsuits, which vary on style, fit, closure system and seam type.
4. Using a thermally instrumented mannequin and flash fire exposure system, to determine if there are differences in <u>thermal protection</u> among the eight garment designs.

NULL HYPOTHESIS

The following null hypothesis was tested to meet objective 4:

There is no significant differences in <u>thermal protection</u> among eight flightsuit designs, varying on (a) style (one piece vs two piece), (b) fit (loose vs tight), (c) type of closure system, and (d) seam type.

DEFINITIONS

<u>FUNCTIONAL APPAREL</u>: Clothing systems that are designed to meet specific functional needs of potential users.

<u>FUNCTIONAL (APPAREL) DESIGN PROCESS</u>: A holistic approach to creating apparel that will meet the physical, social, psychological and aesthetic needs of potential users. The process is based on a strategy control system whereby each step serves as a built-in check in exploration of problem boundaries followed by the definition of the problem structure and assessment and analysis of critical factors.

Design specifications are then developed and analyzed for interrelatedness and priority. Prioritized specifications become the design criteria used for developing the prototype and eventually evaluating its success (Orlando, 1979).

<u>THERMAL PROTECTION</u>: Protection provided by a garment system against heat and flame. It can be measured by small scale thermal protective performance (TPP) testing and/or using a thermally instrumented mannequin and a flash fire exposure system.

<u>(A)Thermal protective performance (TPP)</u>: A rating of protection based on results of a small scale test for high temperature integrity and thermal insulation. The test method used in this research is a modification of ASTM D4108 (open flame method) as outlined in Par 6.1 of CAN/CGSB-155.1-M88, Firefighters' Protective Clothing for Protection Against Heat and Flame. Results generally reflect the effect of fabric thickness and density providing the fabric stays intact.

<u>(B) Thermally instrumented mannequin testing</u>: A procedure which uses a thermally instrumented mannequin exposed to a controlled flash fire exposure system to assess typical skin surface heat transfer rates and potential skin damage to the clothed human body (i.e. to predict the percentage of body receiving skin damage when wearing a garment system).

<u>(C) Operational definition</u>: In this study, thermal

protection is operationally defined by the percentage of the mannequin surface reaching second and third degree burn when exposed to a high heat flux (75.0 kw/m^2) for 3.5 seconds. A higher percent burn indicates lower thermal protection.

FLIGHTSUIT: Workwear used by aircrew members. In this study, both one-piece and two-piece styles are included.

LIMITATIONS & DELIMITATIONS

1. The garments designed for this study are limited to flightsuits to be worn with appropriate thermal protective underwear.
2. The study is limited to the design of flightsuits for males.
3. The focused group interview was conducted at Canadian Forces Base Edmonton. The non-random sample of participants may not necessarily represent pilots in the Canadian Forces.

ASSUMPTIONS

1. The fabrics selected for TPP testing in an earlier research phase are representative of what can be used for thermal protective flightsuits by Canadian Forces Personnel.
2. The participants in the focused group interview provided valid subjective data regarding the flightsuits and activities.

CHAPTER 2

LITERATURE REVIEW

It is known that burn injury was a major source of morbidity and mortality during World War II (Leung, 1988), and is still the primary threat in those professions with high fire risk. Fire is the most serious danger faced by aircrew in the course of a flight mission. Therefore thermal protection is one of the most critical factors in protective clothing used for fire fighters, pilots, industrial workers and others likely to be exposed to intense heat. Besides thermal protection, other criteria such as comfort, fit, mobility, aesthetics and production factors have proven to be important factors in design of thermal protective flight suits.

The literature review for this study is divided into five sections. The first section is a review of the principles of heat transfer and skin damage, which explain how the heat is transferred and the relationship between heat transfer and skin damage. A review, comparison and evaluation of flammability and thermal protection test methods and research using such methods follows. A third section reviews the literature on burn accidents involving pilots. The literature on thermal protective fabrics & thermal protective garment design follows, emphasizing research on thermal protective flightsuits. Literature on various design processes is reviewed in the final section.

The functional apparel design process which served as a framework for this study is discussed in detail in Chapter 3: Functional Apparel Design Process.

Heat-transfer and Skin Damage

One important element in studying thermal protection is to understand the principles of heat-transfer and skin damage. Heat may be transferred to the skin by radiation, convection, conduction or any combination of these mechanisms. The most significant way that heat is transmitted is by thermal radiation, which is expressed in kW/m^2 or $cals/cm^2.sec$. The amount of heat transferred by thermal radiation depends upon the temperature difference between two surfaces, their distance from each other and the reflectivity of each surface (Chouinard, Knodel and Arnold, 1973; Leung, 1988; Veghte, 1981).

Another important mode of heat-transfer is by convection. Heat transmission by convection depends on the movement and density of surrounding gases or liquids. Air convection not only affects the number of calories of heat hitting the clothing, but also the transfer of heat within layers of clothing, and between these layers and the body. Heat transfer by conduction depends on direct contact between surfaces. Heat flows through the resulting continuity of surfaces. It is significantly increased if protective clothing is wet or compressed (Veghte, 1981).

As the skin heats up to an average surface temperature of 33°-35°C, the sweating mechanism begins (Veghte, 1981). About 50% of sweat is derived from the trunk, 25% from the lower limbs and the remainder from the head and arms (Veghte, 1982b). Evaporation of sweat from the skin and respiratory passages is the reason human bodies are able to withstand air temperatures up to 205°C. If the sweating mechanism's buffering effect is overwhelmed, tolerance time for the caloric load is elapsed, and skin temperature rises above the pain threshold of 48°C. Blistering then follows. The skin is a reliable indicator of the thermal load if it is exposed, such as on the face. Veghte (cited in Veghte, 1981) gave an example that in U.S. Air Force experiments subjects wearing Nomex® flight clothing could approach within 6 to 10 meters of JP-4 fuel flame fronts projecting 71 kW/m^2 (1.7 cal/cm^2 sec) thermal radiation before intolerable subjective pain was experienced on their faces.

Thermal damage to the skin occurs as a result of an increase in tissue temperature above an injurious level within a finite period of time. The severity of burns depends on the intensity and duration of exposure (Leung, 1988; Veghte, 1981). Protective clothing increases the time to pain and lowers thermal damage to the skin.

Thermal Protection Test Methods

A significant amount of research on thermal protective fabrics and garments has been published. These studies, however, provide insufficient information, since few of the studies have been conducted using the same conditions of testing. Therefore, a literature review on the test methods was required for this research on thermal protection of flightsuits. The strategy of this review was to compare and assess the utility of the different thermal protection test methods which have been published. The focus of the literature review is to evaluate test methods based on two criteria: the extent to which the tests approximate field exposure and the usefulness of the tests as means of differentiating among the burning behaviours that are characteristic of the range of materials used in protective suits (Brewster, & Barker, 1983; Crown, Rigakis, & Dale, 1989).

To assess the protection from heat and flame, two factors, flame resistance and thermal protection, are most important. Flame resistance testing is a preliminary step to measuring thermal protection by TPP tests. The concept of thermal protection comprises several aspects such as thermal insulation, thermal integrity and thermal shrinkage. Each of these factors must be taken into account in testing.

Flame Resistance

Fibre ignitability is just one of many factors which characterise the flammability or flame resistance of fibres and fabrics. Other factors which need to be considered are rate of flame spread, molten drip, production of char, production of smoke, production of toxic fumes, afterglow, shrinkage and splitting, and type and extent of damage (Buxton, 1989).

Many flame-resistance and flammability tests have been developed. Among these, vertical flame tests provide simple assessments of flame resistance. These tests measure the resistance of textile fabric to burning when a flame is applied to the lower edge or the surface of a vertical specimen. The occurrence of flashing over the specimen, the duration of afterflame, the duration and location of any afterglow, and the length of the damaged area may all be noted. A variety of vertical test methods have been developed.

In the American Federal Test Method 191A 5903, a 3.8cm (1.5 inch) flame is applied to the bottom edge of a vertically oriented specimen for a maximum exposure time of 12 seconds; after-flame time, after-glow time and char length are determined (cited in Brewster & Barker, 1983). This method and similar ones have been widely employed. A common weakness is that the contact with the flame occurs at a cut edge of the test specimen and both surfaces of the specimen are engulfed in the flame. Such a flame exposure does not truly represent the fire contact encountered in the field, where the flame frequently contacts only the outer surface of the suit material. Therefore the International Organization for Standardisation (ISO) developed a surface ignition test. A modification of this method has been adopted by Canadian General Standards Board (CAN/CGSB-4.2 No.27.10) and is cited for use in both Fire Fighter's Standard and Canadian Petroleum Association's (1991) Performance Standard for Thermal Protective Clothing.

Instead of contacting the test specimen at the lower edge, the ISO test surface ignition method positions the burner perpendicular to the surface of the vertical specimen so that the axis of the burner is 20 mm above the lower edge of the specimen frame and the flame contacts the specimen at its surface. For edge ignition tests, the ISO method positions the burner at 30° to the vertical. These methods remedy the defect of the other vertical tests.

One critical factor which should be considered is that different flame resistant fabrics afford different degrees of protection to a wearer under conditions of fire. The flame resistance tests, however, indicate little difference among flame resistant fabrics. Since most high performance fabrics have good resistance to a vertical flame, in other words, they do not propagate flame after removal of the igniting source, and have relatively short char lengths, evaluation of these materials on the basis of these tests alone can be misleading. To emphasize differences that exist among flame-resistant fabrics, investigators have increased the severity of the vertical tests by using prolonged exposures or hotter ignition sources (Brewster and Barker, 1983). In these cases, flame resistance is discussed in light of the extremely severe heat assaults occurring during exposure to intense flame.

Another useful indication of the differences among flame-resistant fabrics is a quantity called the Limiting Oxygen Index or LOI. The interpretation of flammability in terms of the oxygen index has been much discussed. According to Abbott and Schulman (1976a), LOI is the minimum oxygen concentration in an oxygen/nitrogen mixture supplied under controlled conditions that will enable a fabric strip held vertically in a combustion tube to burn at a slow but steady rate after removal of a flame ignition source. The oxygen index establishes the minimum volume fraction of oxygen which, when mixed with nitrogen, sustains burning of the fabric. Thus the higher the LOI, the better the flame-resistance. This test is essentially different from a simple vertical burn, both from the standpoint of the direction of the flame impingement and the environment of combustion. It is generally thought that the procedure provides a useful quantitative measure, particularly valuable in the case of differentiating flame-resistant materials. Abbott (cited in Brewster and Barker, 1983) reported the oxygen indexes of a number of different protective fabrics in his research on "Nonflammable Fibres". These data show that fabrics from PBI® (polybenzimidazole) and Durette® (novoloid) have higher oxygen indexes than more commonly used materials, such as

Nomex® or flame resistant cotton. It is not always clear, however, how these ratings translate to the protection afforded.

Thermal Protective Performance

Traditional flame resistance tests of textiles, such as the vertical tests, provide insufficient technical data and are especially limited for evaluating the protective performance of modern, highly flame resistant fabrics. They alone cannot indicate the thermal protection capacity but rather are used as a screen or preliminary step to measuring protection. Some fabrics are flame resistant but would offer poor thermal protection due to low thermal integrity or low thermal insulation. The poorest fabrics from preliminary flame resistance testing should be eliminated before doing further testing or assessing other criteria (Crown and Rigakis, 1989).

If a fabric in a protective garment leaves little structural residue when exposed to intense heat, the skin or underlayers are left exposed and burns can be severe. By contrast, a fabric that maintains its structural integrity through pyrolysis and char formation, continues to protect the wearer (Brewster and Barker, 1983). Thermal integrity, or retention of structural integrity following exposure to heat, has been studied. Abbott and Schulman (1976b) in one experiment measured the retention of fabric strength at different levels of radiant or convective exposures. The fabrics were exposed to radiation from quartz panels while the retention of strength was measured using an Instron tensile tester. In tests made on meta-aramid fibre, flame-resistant cottons, and novoloid fabrics, a rapid strength loss was observed even at low exposure levels. At heat flux levels approaching 42 kW/m^2 (1.0 $cal/cm^2/sec$), all fabrics tested lost at least half of their strength in less than three seconds exposure. Fabrics were also exposed in a circulating hot-air oven to determine the degradation in this type of heating. In the convective exposures, most of the fabric strength and integrity were lost when the oven temperature was raised to over 300°C.

It is important that the fabric resist shrinkage at elevated temperatures, since the potential for burn injury may be greatly increased by the elimination of insulating layers, air pockets and by contact with the skin, even if the fabric does not ignite and burn. In Freeton's experiments of shrinkage of Nomex® and PBI® (cited in Brewster and Barker, 1983), he found that the amount of shrinkage increases with the temperature of exposure, exceeding 10% above 415°C. PBI® fabrics shrank about one-half as much as Nomex® fabrics. At temperatures above 426°C, the Nomex® fabric was badly charred and curled, making an accurate measurement of shrinkage difficult. At temperatures approaching 500°C, most of the PBI® samples exhibited curling and embrittlement, although a thermally stabilized sample of PBI® shrank 35% at the highest test temperatures. These exposures simulate severe conditions (Brewster and Barker, 1983).

Even with good thermal integrity and good resistance to thermal shrinkage, a garment of single layer or low thickness fabric will provide less protection at the same exposure level than multi-layers of the same fabric or various fabrics used in combination. It is generally thought that heat transfer or thermal insulation depends on the thickness and density of the fabric. Barker, Stamper and Shalev's study (1988) concluded that decreasing the effective thickness of compressible fabrics can cause the thermal insulation to be reduced and the rate of heat transfer to increase. The insulative values of garments should be such that the heat transferred through the clothing during exposure will be below the level at which serious discomfort or skin injury will occur. The transfer of heat through the assembly of fabric layers making up clothing is a complex combination of the effects of radiation, absorption, conduction, and reflection of thermal energy (Abbott, 1977). Therefore measuring the heat transferred to the wearer rather than simply relying on characterization of flame support or material damage, will provide a more useful index of thermal protective performance.

Laboratory based measurements of heat transfer through fabrics have been facilitated by the standardization of simple calorimetric test methods and the development of a scientific basis for translating heat flux measurements to predict the severity of the injury to human tissue (Shalev and Barker, 1984). Many experimental apparatus of various designs have been constructed to measure heat transfer through protective fabrics exposed to radiant and to convective heat. Most are designed to allow time controlled exposures to regulated heat sources and to provide a means of measuring the thermal response of the fabric. The basic components consist of a heat source, a heat sensor, and support equipment including sample holders, timing and recording systems. The utilization of newer materials and constructions to provide protection from flames and heat has resulted in the identification of a need for suitable test methods to accurately reflect the occupational exposure conditions (Day, 1988).

The American Society for Testing and Materials (ASTM) developed method D4108-82, Test Method for Thermal Protective Performance (TPP) of Materials for Clothing by Open-Flame Method. This test is not applicable to textile materials that undergo complete flaming combustion when tested vertically for flame resistance. The method rates textile materials for thermal resistance and insulation when exposed to heat flux of 84 kW/m^2 (2 $cal/cm^2/sec$). A horizontal specimen is exposed to a prescribed flame from a gas burner placed beneath it. The amount of heat passing through the specimen is measured by means of a copper calorimeter placed behind the specimen. The temperature increase of the calorimeter as a function of time is used to determine the exposure time required to cause pain and second degree burn or blister in accordance with specified burn criteria developed by Stoll and Chianta (1969). Based upon the total heat exposure, determined from the time and the exposure level, a direct measure of the protective capabilities for the specimen can be obtained. This rating is called the Thermal Protective Performance or TPP rating. The TPP rating is twice the time (in seconds) that it takes the sensor to reach the second degree burn criterion. For example, a TPP value of 10 suggests 5 seconds to reach second degree burn when exposed to a heat flux similar to that of the test.

A modified version of the ASTM method is utilized by the National Fire Protection Association (NFPA). Day (1988) reported the test results obtained from the standard ASTM test method and modifications of it and suggested that although classified as modified version of ASTM (D4108-82), the NFPA-1971 method does have several important differences. For example, it uses two burners and a bank of 9 quartz tubes instead of a single burner as in the ASTM method. Day also showed that an air gap resulting from a spacer between fabric and calorimeter greatly reduced the heat transfer leading to higher TPP values. Because of possible distortion of the fabric from its initial planar configuration, this air gap can change dramatically during exposure; therefore, it poses several problems especially if the data are to be used in garment performance specifications. In comparing several versions of the TPP test, Day (1988) found that the nature of the source of heat flux does not appear to be as important as the manner of specimen mounting in determining the heat transfer through fabric assemblies. The use of a restraining frame appears to offer the advantage of preventing thermal shrinkage, and such a modification of ASTM D4108-82 has been adopted in the Canadian standard for protective clothing for fire fighters. It has been used by the Clothing and Textile Department, Textile Analysis Service at University of Alberta in its "TPP" tests.

Thermally Instrumented Mannequin

The testing described above has been done on small pieces of fabric specimens. Garment flammab'lity research developed out of recognition that garment burning behaviour and flammability hazard could not be accurately predicted from small-scale fabric tests and individual materials alone. In order to realistically assess thermal protection from burn injury, the testing must be extended to the clothing system as a whole. Much work has been done to try to compensate for the deficiencies in testing. Since the 1960's a substantial body of published literature has documented the use of whole garments, principally in research rather than routine testing. Most garment testing has been on human-like forms, primarily mannequins (Norton, Kadolph, Johnson and Jordan, 1985).

Perhaps the earliest use of human-like forms in garment flammability testing was in the 1940's. Baker and Smith compared burning rates of shirts on mannequins in forensic work at that time (Baker, 1978). Colebrook and Colebrook (cited in Norton, Johnson and Jordan, 1984) described garment tests on a wire body form. Thermal instrumentation of mannequins for clothing research apparently followed much later. In 1962 Stoll reported fuel-fire tests by the U.S. Navy on a leather-covered mannequin equipped with temperature detector paper and melting point indicators. On the basis of previously obtained temperature-time data on skin burns and the placement of temperature detector sites, measured temperatures yielded predictions of burn severity and extent in fire exposures. Researchers with the US Naval Air Development Centre also did much of the early work in this area using mannequins which were dressed in the clothing system under investigation and then exposed to open flame. More recently Dupont Laboratories in Wilmington, Delaware use a mannequin they call Thermo-Man®. The instrumented mannequin was originally designed and developed by the Aerotherm Division of the Accurex Corporation under U.S. Air Force contract, for use in determining the burn protection of flight suits. The mannequin is equipped with 120 thermocouples covering its entire surface. The mannequin is dressed and exposed to intense flame and heat sources. It uses sophisticated heat sensing instrumentation to provide substantial information on the ability of garment materials to protect against 2nd and 3rd degree burn injury. In addition to observing the burning behaviour of the clothing, it is possible to measure the amount of heat received at the body surface over a given period of time. The most recent additions, an intense heat delivery system capable of simulating a military or industrial fire hazard and a sophisticated computer system for analysis of the thermal output data from the mannequin, allow the Thermo-man® system to be used in unparalleled evaluation of thermal protective performance of full clothing systems subjected to laboratory flash-fire conditions.

Research conducted by Behnke, Geshury and Barker (1992) used the Thermo-Man® and the Thermo-Leg evaluation systems to assess the thermal protective performance of selected garments made of Kevlar® and Nomex® aramid fibers, and of FR wool and FR cotton fabrics. The Thermo-Leg evaluation system was developed to evaluate the thermal protective performance of garments that are simultaneously subjected to fire and to dynamic leg movement. The centre of the system is a full size (size 40) fiberglass-epoxy molded leg. Eighteen heat sensors, similar to Thermo-Man® sensors, are distributed over the entire surface of the leg. Biomechanical and kinesiology studies of human leg action in running were used to design the movement of mechanical leg to provide a precise simulation of running motion. The research employed a computer and a data acquisition unit to analyze the thermal output data from the mannequin and the Thermo-Leg (Behnke, Geshury & Barker, 1992).

Thermal instrumentation greatly enhances the ability to predict garment flammability hazard or protection in fire simulations by permitting the prediction of burn injury on the human body. The development of thermally instrumented mannequins for apparel flammability research has depended on two lines of work. One of these is of a methodological nature, involving materials and methods for constructing mannequins, the accompanying instrumentation, and procedures for analysing and interpreting temperature or heat flux data obtained from mannequins (Norton, Kadolph, Johnson and Jordan, 1985). The mannequins designed for research differ with various studies.

At the University of Minnesota, an adult female thermally instrumented mannequin referred to as Minnesota Woman was used for apparel flammability research. Forty-four chromel-alumel thermocouples (0.13 mm diameter) were encased in Pyrex, with measuring junctions exposed, and installed to measure surface temperatures during garment burnings. The degree of injury was predicted from time-temperature relationships at skin layer boundaries according to criteria established by Henriques and modified by Stoll and Greene (cited in Norton, Kadolph, Johnson and Jordan, 1985). Injury extent was expressed as a percentage of body surface area (Norton, Kadolph, Johnson and Jordan, 1985).

An adult male thermally instrumented mannequin has been constructed at University of Alberta for testing the thermal protective qualities of garments when subjected to short duration flash fires. One hundred and ten skin simulant sensors are used to measure the rate of heat transfer to the mannequin surface. The flash fires are produced with propane diffusion flames. A computer controlled data acquisition system is used to run the experiment, record and store the data, calculate the extent and nature of skin damage and display the results (Dale, Crown, Ackerman, Leung, & Rigakis, 1992). The details of mannequin testing will be discussed in chapter 4, Prototype Evaluation.

Burn Accidents Involving Pilots & the Related Clothing Performance

There is very little information available on burn incidents involving pilots. In fact, only one accident report involving a Boeing helicopter in August 1982, has been found by the researcher in the literature search. Detailed information about the burn damage to clothing and related personnel injuries was gathered. McLaren (1985) reported that all three survivors of the helicopter accident suffered varying degrees of burn injury. One man received fairly severe burns to his face and hands. He was not wearing any handwear at the time of the accident. Another man was badly burned on his back and upper legs. It appears that the bottom edge of the back of his jacket caught fire, causing the coverall to burn as well, with the resulting heat ccausing burns to the back area.

All three survivors had varying degrees of burns under layers of clothing. The area of the jacket or coverall corresponding to the area where burn injury was sustained, was burned, or had melted and adhered to the underwear. A close examination of the three sets of underwear worn by the survivors revealed there was no damage to this layer at all, even though all three men suffered burn injuries on areas covered by the underwear.

The underwear included 100% cotton lightweight and polyester/cotton heavyweight longjohns and T-shirts in squadron colours. Several things were noted about the accident. First of all, the underwear protected the wearers since it provided insulation from the heat of fire. The burn injury would have been much worse if the underwear were not worn. Secondly, there was sufficient heat transferred through the underwear to burn the skin underneath.

Thermal Protective Fabrics

FR finishes on cotton

Some FR finishes have been used on some natural fibers to improve their flame resistant qualities. Topical finishes of low-melting salts have a long history and work by either fusing in heat to give glassy, protective deposits or decomposing to give off non-flammable vapours (Ford, 1989). However, these finishes are not washfast or rainfast, spoil fabric handle, and are often dusty.

Other finishes containing phosphorus are in widespread use for the production of flame retardant cotton. One such finish used for cotton workwear in both Europe and USA is Proban•, made by Albright & Wilson. Chemically similar finishes command most of the FR-cotton market in the USA.

FR finishes for wool

A successful finish for wool is Zirpro• developed by the International Wool Secretariat. This is a complex of titanium or zirconium applied and fixed inside the fibre. Zirpro• is used in many kinds of heavy workwear, such as firemen's tunics. Zirpro• treated wool is also employed to protect men working at furnaces and in steelmaking as it offers good resistance to splashes of molten metal (Buxton, 1989).

FR viscose

FR viscose fibre incorporates spun-in components containing phosphorus. The use of FR viscose in fibre blends is increasing, either to reduce cost in conjunction with a more expensive fibre, or to improve wearer comfort by adding moisture absorbency (Buxton, 1989).

Aramid fibres

The first commercial fiber in this generic class was the meta-aramid fibre Nomex®, developed by DuPont in 1961. It is a principal synthetic FR fibre that is in widespread use in protective workwear. However, since garments made from 100% Nomex® may feel hot, and fibre-splitting and shrinkage may occur on heating Nomex® severely, some needs for modification emerged. Blended with FR viscose (e.g., 65/35 Nomex®/FR viscose), the poor thermal comfort of the fabric can be corrected at the expense of some abrasion-resistance. The defect of intumescence or fibre-splitting and shrinkage that the original Nomex® displayed when exposed to severe heating can be rectified by blending with the alternative para-aramid fibre Kevlar®. Blends of the meta and para varieties can provide higher tenacity, as a result from the strong para component, and do not exhibit as severe heat shrinkage. Some commercial blended yarns are available for thermal protective clothing. They include Nomex III® (95/5 meta/para aramid), which is said to be somewhat intumescent (Buxton, 1989), and a more stable but more expensive 50/50 blend. Nomex® Plus (65/35 Nomex®/FR viscose, no longer marketed) had a lower price but lower abrasion-resistance. Teijin Conex® is a meta-linked aramid fibre with broadly similar properties to those of Nomex® and finds uses in flame-resistant clothing (Ford, 1989).

Polybenzimidazole

Another fibre with extreme resistance to heat and flame is PBI® or polybenzimidazole. The outstanding characteristics of PBI® are not only its great high temperature resistance (e.g. normal performance to 350°C), but also its non-production of smoke to 550°C and a high LOI value of 41 percent (Buxton, 1989). Furthermore, the PBI® marketed today does not melt, shrink or become embrittled with heat. For a synthetic fabric, PBI also has the unusually high moisture regain of 14%. The fibre therefore offers considerable garment-comfort advantages over most other synthetic fibres. Owing to its moderate mechanical properties, PBI® is often combined with stronger fibres, and a modern firefighting fabric in the USA is 60/40 Kevlar/PBI®. PBI®/FR viscose blends are exploited for workwear, and form a metallising substrate for fabrics for proximity suits. However, the price of PBI® is generally higher than other synthetic fabrics such as Nomex® (up to four times the price of Nomex®) (Ford, 1989).

Since the late 1980's, PBI®/Nomex® blends have been commercially available and are claimed to be the best suited to meet the stringent requirements for the future generation of military apparel. Besides their outstanding protective qualities, testimonials from various wear trial participants also confirmed the improved comfort and reduced heat stress of the PBI® blend garments due to the high moisture regain. It was claimed that the fabric was the first flight suit improvement in 20 years.

Thermal Protective Garment Design

The choice of fibre has a fundamental effect on the thermal protection of clothing. However, both burning behaviour and protection qualities are greatly modified by fabric structure, garment design, and arrangement of garment layers (Ford, 1989). Garment design has been realized to be an important factor that can greatly affect the thermal protective properties of garment.

In his research on the design of protective clothing for firefighters, Veghte (1981) realized that the traditional coat and pant ensemble provided little or no protection for the lower body due to faulty design. For example, in waist type pants, elastic material around the waist may not be functional because it can melt even though covered by the coat. Furthermore, it compresses the multi-layer fabric configuration against the body which eliminates vital air spaces between layers and enhances undesirable conduction of heat. To solve the problems, Veghte suggested the pant bib to contain all the layers of fabric, not just the Outer shell; extra layers of outer shell fabric and a thermal liner should also be used at the knees to delay conductive heat gain from compression when kneeling in addition to providing extra abrasion resistance.

Thermal Protective Flightsuit

In the 1960's, researchers at the US Army Natick Laboratories were requested to design an improved fire resistant combat flight coverall for the US Army aircrew members in Vietnam. The original "Nomex" flight coveralls tested in Vietnam in 1966 were determined unsatisfactory for wear because of physical discomfort and irritation caused by the coarsely woven fabric. Thermal protection provided by the flightsuit was also insufficient because "there is no textile material available at this time which, in single layer, will provide a significant degree of protection against gasoline fires" (Oakes & Maj, 1967, p. 2). It was suggested that the lower part of the body and the back are the areas which are most susceptible to ignition, and therefore should be a double layer (Oakes & Maj, 1967). The new coverall was made of a closer, smoother woven Nomex® material designed to be less irritating. Several design changes were made in the coverall to correct deficiencies in the previous design. However the double layered flight coverall was considered by the evaluators to be warmer and less comfortable than the standard Army flightsuit.

In 1970, the Fibrous Materials Branch, Nonmetallic Materials Division of the U.S. Air Force Materials Laboratory conducted research evaluating several candidate fabrics for American flight suits. Mannequins clothed in various coverall fabrics were examined for average percent body area burned where second degree or worse burns occurred. Untreated cotton and fire retardant treated cotton flight suits resulted in an average of greater than 60 percent body area burned. Nomex coveralls resulted in greater than 30 percent average body area burned. Polybenzimidazole (PBI), an experimental fibre developed by the Air Force Materials Laboratory, resulted in an average less than ten percent body area being burned (Schulman & Stanton, 1971).

In the late 1970's, a program undertaken at the U.S.A.'s Naval Air Development Center (NADC) developed a double-knit high temperature resistant aramid fabric for flight coveralls. Due to the inherent characteristics of knits, the improved fire resistant garment was produced at lower cost than using new, more expensive, exotic fibers. Other favourable characteristics of knit constructions as compared to woven fabrics include more freedom of movement, better fit and aesthetic appeal, and improved comfort. Undesirable features were that the fabric stretched and became baggy when worn for extended periods, and that the fabric was prone to snagging (Lewyckyj and Reeps, 1978). The Navy Clothing and Textile Research Facility (NCTRF) developed a flyer's blue aramid coverall in the mid 1980's, at the request of the Naval Air Systems Command (NAVAIR).

The fabric used was a piece-dyed 95/5 meta/para aramid material. The coverall design was the same as that of the Air Force CWU-27/P coverall (Flyer's Summer Fire-Resistant Coveralls), except that a pencil pocket flap and shoulder epaulets were added. A set of Navy patterns with a size range of 32 short through 48 long was developed for the coverall. Twelve garments were tested for protection against fire at the NADC fuel fire test facility. A mannequin dressed in the coverall was carried through the flames on a rotary crane with a 2-second traverse over the fire pit. The testing results showed that all but one of the coveralls was flaming as they emerged from the fire pit, and all quickly self-extinguished. The mean percentage of the body burned at 250^0F for the 12 coveralls was 26.83%. The coverall offered average protection from fuel fires. Since the flight coverall is usually covered by any number of additional pieces of equipment and sometimes by an outer garment such as a jacket, the actual protection offered by the entire system would be greater than that offered by the coverall alone. Thus, the flyer's blue coverall seems to offer adequate flame-resistance protection when worn with the entire system of flight clothing. Therefore, NCTRF recommended adoption of the Navy flyer's fire-resistant blue coverall as an option (Boutin, 1984).

Design Process

In his Design Methods, Jones (1981) commented that designing is a hybrid activity which depends upon a proper blending of art, science and mathematics and is most unlikely to succeed if it is exclusively identified with any one. In designing a protective garment, incorporating the relevant factors is a complex task. It is objectifying the design process to make the resulting design meet specific needs (Orlando, 1979). A simple way of discussing the differences between design methods and trying to judge their usefulness in practice is to review the methods as representing three points of view: that of creativity, that of rationality and that of control over the design process. From the creative view point the traditional designer is like a "magician" or a "black box" out of which comes the mysterious creative leap. The most valuable part of the design process is that which goes on inside the designer's head and partly out of reach of his/her conscious control. It is an intuitive approach that the designer produces his/her output without being able to explain how a design idea has developed (Dejonge, 1984). In his research on fire fighter's protective clothing, Veghte (1982a) stated that "prior to the 1940s, most of the input and ideas concerning the design of firefighter clothing were subjective and based on the individual's own views and experiences" (p. 45). According to Branson (cited in Van Schoor, 1989), the design process traditionally used for apparel is one based on the creative inward assimilation of inputs in the designer's head.

The extreme opposite of the "black box" approach, in other words, from the rationality view point, is what Jones (1981) called "glass box" designing. This system is considered to be systematic and objective. Designers are concerned with externalized thinking and designs are therefore based on rational rather than on intuitive assumptions. Many parts of the system the designer investigates are visible. In this approach, a designer is much like a human computer, a person who operates only on the information that is fed to him, and who follows through a planned sequence of analytical, synthetic and evaluative steps and cycles until he recognizes the best of all possible solutions. Therefore this method is only valid in the case under a known design situation. Besides, this computerlike process often omits an aesthetic concern and integration of different aspects of the design problem (Orlando, 1979).

The main weakness of both black box and glass box methods is that the designer generates a universe of unfamiliar alternatives that is too large to be explored by the slow process of conscious thought. The designer can neither make an intuitive (or black box) choice, nor use a high-speed computer to search automatically (Jones, 1981).

Therefore, Jones proposed "the self-organizing system" which, from the control viewpoint, combines those two extremes - one part carries out the search for the design (creative process) and the other controls and evaluates the pattern of search (strategy control). It is through this final approach that Orlando's functional apparel design process was developed.

CHAPTER 3

THE FUNCTIONAL APPAREL DESIGN PROCESS

Conceptual Framework

Described as an "externalized, systematic, holistic approach to clothing design used primarily in the development of special purpose apparel" (Van Schoor, 1989), the functional apparel design process, as developed by Case and Orlando (1979), served as the conceptual framework for this research. The design process begins with a general request for the design. A problem is usually identified in general terms outlining the nature and purpose of the garment, such as "clothing for active sports" or "chemical protective clothing".

Then the design situation is explored thoroughly and nonstructurally to identify as many areas and directions for further design improvement as possible. This stage acts to extend "the boundary of a design situation so as to have a large enough, and fruitful enough, search space in which to seek a solution" (Jones, 1980). It is a common fault in designing to skip this stage and try immediately to define the specific problem. When a designer moves too quickly to define a "problem", the true problem may be missed. A number of possible research strategies can be used at this stage of the research. A general objective statement for the study can be developed and used to explore all relevant aspects of the constructed, the behavioral (i.e, users' activities and attitudes) and the natural work environments. Other strategies include user observation, brainstorming and literature search in general terms. These strategies provide a wide background and clear design situation for the study.

The problem structure perceived stage is a transformation from the entire spectrum opened through divergence to focal areas of design concern (Orlando, 1979). Literature search at this stage narrows to specific critical factors. Other strategies such as user interviews, observation analysis, market analysis and activity analysis will also play decisive roles. These strategies will all converge and the problem will be defined.

The designer/researcher then assesses the critical factors identified for the specific problem to arrive at design specifications. The number of factors and depth of inquiry will vary with the problem being studied (Orlando, 1979). Specifications are listed to "externalize" all of the features considered to be desirable for the design.

The interactions of design criteria are established by charting, ranking and weighing the design specifications to set priorities for the garments' design. To discover interactions among the design specifications derived in the previous stage, an interaction matrix can be used to illustrate specifications that are in direct conflict, those that require accommodation to be met in the same design, and those that create no conflict when grouped together

(DeJonge, 1984). Specifications that need additional attention in determining the outcome of the garment design are outlined by converting the matrix into an interaction net.

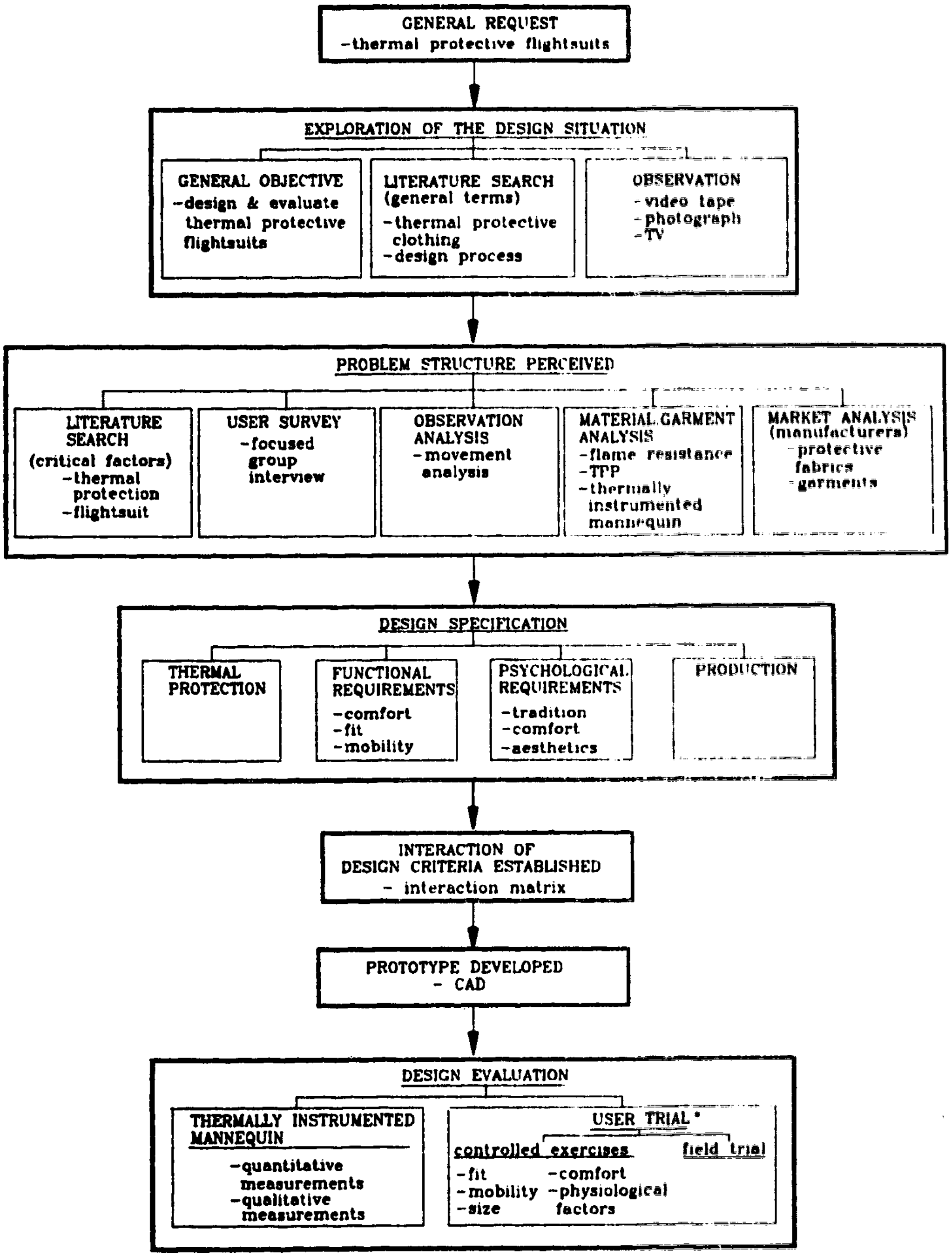
A list of design specifications ranked in order of priority becomes the guide for the designer in the next stage of the design process: prototype development. The prototypes are developed and tested to ensure that the design will meet the established design criteria. The creative integration of criteria leads to possible solutions, which are then evaluated against the list of established criteria to determine what will be incorporated in the final design (DeJong, 1984).

The final step of the process is design evaluation. Evaluation is based on the results from the previous stages. The evaluation will usually consist of both objective evaluation of the design and user's subjective evaluations of the performance of the garment.

Figure 1 outlines the design process and the design strategies developed specifically for the problem in this study. Each step is elaborated below.

General Request for the Design

To outline the nature and purpose of the garment developed in this study, the researcher identified the general request for the design as "to design flightsuits to provide optimum thermal protection for Canadian Forces



* to be conducted in later phase of research.
Figure 1. The functional apparel design process.

flight personnel". Specific requests regarding the flightsuit designs had been made by Defence Research Establishment Ottawa who support the project. Four parameters of interest were specified for evaluating their effect on flightsuits' thermal protection: one-piece vs two-piece construction, loose fitting vs close fitting, closure system and seam type.

Exploration of the Design Situation

This phase of the research involved exploring the design situation thoroughly and nonstructurally. It included stating general objectives, searching the literature in general terms, and observation.

The general objective was based on the general request and defined as "design and evaluate thermal protective flightsuits for Canadian Forces flight personnel". More specific objectives identified for this research were outlined in Chapter 1.

The literature search at this stage was broad and general. It focused on such general concepts as thermal protective clothing, and included literature on clothing for various occupations needing thermal protection, such as firefighters, petroleum workers and pilots. Relevant aspects of the research such as the thermal protective properties of fabrics and garments, clothing comfort and fit, interview techniques, garment (system) design, testing methods for thermal protection and flame-resistance were also included in the literature reviewed. Literature on the design process was also reviewed at this stage.

To explore the design situation thoroughly, another important strategy used at this stage was observation of both video tapes and photographs of previous mannequin testing of thermal protective clothing. The video tapes and pictures of the mannequin testing for petroleum workers' coveralls displayed the body structure of the thermally instrumented mannequin, the simulated flash-fire system, the styles of the garments that were tested, and afterflame occurring during the testing. Watching a TV program about American pilots and planes called "Flying the Heaviest" was helpful. With a small knitted stand-up collar, the American flightsuit looked neat and clean. It covered the neck area well even when the front zipper was open somewhat. The pilot's movement in flight was particularly observed. The pilot frequently stretched his arms to reach the instruments around him inside the cockpit when he was operating an aircraft. It was noted that the American flightsuit has a flange in the back of shirt to accommodate the movement.

When all these pieces of information were combined, the researcher had a clearer picture of the design situation.

Problem Structure Perceived

In this phase strategies such as user interviews and observations, a more detailed literature search about critical factors, material & garment analysis and a market analysis were used in order to perceive the problem structure for the research in more details.

Literature Search

At this stage the literature search focused on the critical aspects of the research: flightsuit design, thermal protection and the functional design process. This review has been summarized in Chapter II.

The literature review on "thermal protection" mainly included two aspects: small scale thermal protective performance (TPP) testing and thermally instrumented mannequin testing with a flash fire exposure system. In this study, mannequin testing is considered the most important element in terms of evaluating thermal protection of different flightsuit designs.

Serving as the frame work of the study, the functional design process was one of the key factors in the literature search. Beside discussing the principles and concepts of the design process, the literature search also focused on other research that applied the functional design process in garment design and evaluation for various problems.

Little literature was found specifically on flightsuit design, perhaps because of the confidential and non-accessible nature of military research. Some literature on thermal protective flightsuits and flightsuit design was found by conducting a computerized search of authorized aerospace and government document databases. Much of this literature focused on the thermal protective properties of various fabrics. Few authors used a thermally instrumented mannequin in evaluating the thermal protection of flightsuits, nor have they discussed the influence of garment design in terms of improving thermal protection. The significance of this study, therefore, is to determine how different garment designs affect thermal protection of flightsuits by using thermally instrumented mannequin testing, considered to be the most appropriate method to evaluate the garment's integral thermal protection.

Focused Group Interviews

Focused group interviews were conducted at CFB Edmonton. A non-random sample of eight to ten aircrew members was selected for each of two interview groups. One group was helicopter pilots, the other was transport pilots. The interviewer asked each person to write down both his likes and dislikes about current and past flight suits, and then to report them verbally. After a discussion of all the responses, participants were asked more specific questions about garment (flightsuit) design. The interview protocol, including recruitment notice, information for participants and consent form (Appendix 1 & 2), was approved by the Faculty of Home Economics Ethical Review Committee.

All participants reacted very favourably to the interview, especially the helicopter group, who were happy to have someone to complain to about their current flightsuits. The helicopter pilots now have one-piece blue flightsuits, two-piece green flightsuits (shirt & pants) and winter jackets. The transport pilots currently have only the one-piece garments and winter jackets. The likes and dislikes regarding current flightsuits are summarized in TABLE 1.

In general, the pilots participating in the focused group interviews thought that fit, comfort and safety are the three most critical criteria in terms of flightsuit design. A pilot in a well-fitting garment will have a neat appearance and feel confident. A more complete range of sizes is needed for both one-piece and two-piece flightsuits to fit pilots better. Comfort is another important concern about flightsuits. Both flightsuits are currently constructed in a 65/35 wool/polyester blend fabric. Several participants believed that the presence of a high percentage of wool causes the garments to be hot and itchy, this being the most frequent complaint about discomfort of the current flightsuits. Additionally the garments become rougher when pilots are sweating. These discomforts apparently reduce a pilot's working efficiency. From a comfort aspect, participants believed that cotton would be a good choice, but they believed that cotton would not provide appropriate

TABLE 1. Summary of Opinions Regarding Current Flightsuits from Focused Group Interviews

A. Two-piece Green Flightsuit

LIKES	DISLIKES
1. easy to go to toilet when they are in the field	*1. bad fit (limited (sizes)
	*2. big waist
2. many pockets and well placed	*3. too hot & itchy
- slash pocket	
- lower pencil pocket cover	*4. crotch too deep-bad cut
- right arm pocket	
3. clips for map	*5. shirts are too long and too narrow
4. scribble pads on thigh	
5. colour is suitable for military	*7. convertible collar is too floppy and gets in the way when they have shoulder belt
6. velcro cover on pencil pocket	
Note: This flightsuit was worn by pilots with the shirt tuched into the pants and with a belt.	*8. sleeves too tight & too short; cannot roll up sleeves
	*9. back pockets add thickness and are useless
	*10. zippers at lower leg pockets are too high when kneeling
	11. the flightsuit needs dry cleaning; not easy care
	*12. pants pull down and are hard to hold up
	*13. wallet and knife pockets are too long and too low
	14. plastic clips are not thermal protective
	15. poor workmanship

B. One-piece Blue Flightsuit

LIKES	DISLIKES
1. more comfortable fabric	1. colour is not suitable for military uniform
2. less hot (than green one)	*2. no scribble pad
3. fit well	*3. no pocket on right leg
4. pockets and zippers are well-placed	4. hot & itchy
5. adjustable waist	*5. convertible collar is too floppy and gets in the way when they have shoulder belts
6. more familiarity with other countries' uniforms	
7. clips on both legs	*6. no cover on low pencil pocket
8. greater variety of sizes available	
	*7. lower leg pockets are too long
	*8. sleeves too tight & too short; cannot roll up sleeves
	9. no thermal protection after washing
	10. poor workmanship

* items considered important in the new design.

thermal protection, which is so critical for flightsuits.

One participant in each interview group had experienced a fire accident. These experiences changed attitudes toward the importance of a garment's thermal protection for some participants, who had thought that thermal protection was not as important as comfort. The helicopter pilot who had experienced a fire accident reported that after the accident, when he realized how important thermal protection is, he bought thermal protective underwear for himself.

The current wool/polyester blend flightsuits do not provide much thermal protection either. Some participants thought that Nomex® would provide the safety that flightsuits require. Nomex® was preferred by some participants, even in terms of comfort, over their current wool/polyester flightsuit.

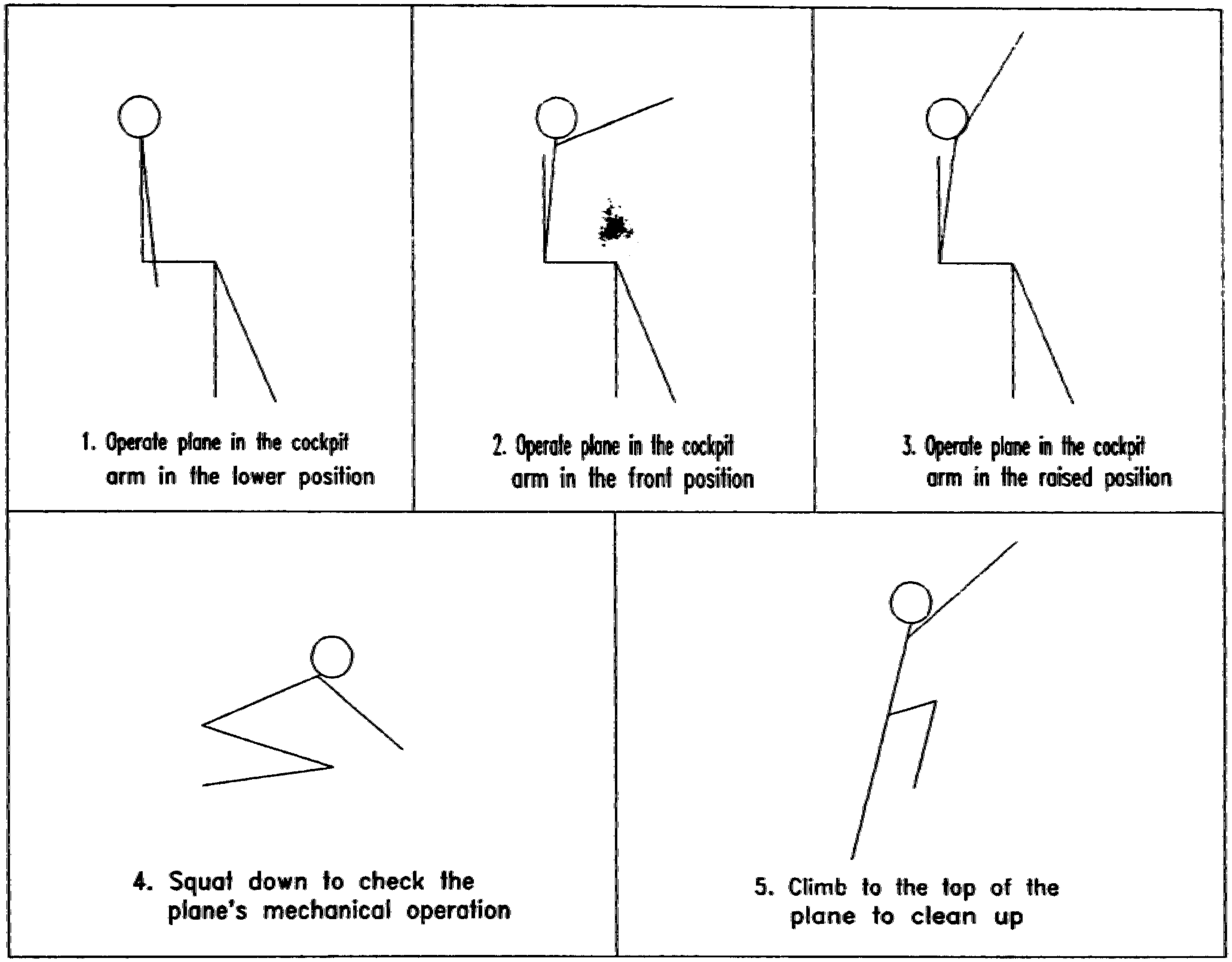
Garments with adjustable features such as Velcro® adjustments at waist and cuffs were suggested by participants for better fit. Abundant pockets on flightsuits are a necessary feature. Because it is inconvenient for pilots to bring briefcases or bags with them when they fly or work in the field, all their personal accessories and tools need to be accommodated in the various pockets on their suits.

Movement Analysis

Video taping was used after the focused group interview to record movement for analysis. Two pilots from each group were asked to simulate their typical daily activities in and around their planes, wearing their current one-piece and two-piece flightsuits. Stick figures (Figure 2) were developed for the movement analysis. When pilots are operating aircraft in the pilot's cockpit, they need to stretch their arms ahead of them and above their heads to reach the operational instruments. The arms' movement can be described as flexion around the shoulder in a half circle from bottom through front to top (Figure 2, "1"-"3"). The garments therefore need to provide enough allowance for arm movement. From the video tape, it could be seen that the flightsuits the pilots were wearing were stretched both at the back and the underarm, especially when they were raising their arms, preventing the pilots from moving their arms comfortably. Helicopter pilots have to do many tasks in the field other than flying, such as squatting to check the helicopter's mechanical operation or climbing to the top of the helicopter to clean up (Figure 2, "4" & "5"). Therefore, accommodation of movement in their activities is required in the design of flightsuits.

Market Analysis & Material Analysis

A market analysis and a material (& garment) analysis were completed in an earlier project (Crown & Dale, 1992). A survey of FR materials and finishes that are available for use in military flightsuits and/or underwear was undertaken. Suppliers of FR fibres/fabrics were contacted for samples,



<u>Figure 2</u>. "Stick figure" of pilots' typical movements in & around their planes.

literature and specifications on FR materials that were considered appropriate for military flightsuits. Results are reported in Appendix A of Crown and Dale (1992).

From the information obtained in the market analysis, seven outerwear and five underwear fabrics were selected for screening using thermal protective performance testing both with and without a spacer. Thermal protective performance (TPP) tests in this project were completed by exposing two-layer specimens to a heat flux of $84kW/m^2$ with and without a spacer between the fabrics and calorimeter. Based upon the results of the TPP testing, three types of outerwear fabrics were selected for further mannequin testing. The three outerwear fabrics, 50/50 FR wool/Teijin Conex®, Nomex®IIIA NCS-106 and 80/20 Nomex®III/PBI®, were sewn into flightsuits. The pattern followed the current one-piece military flightsuit, which was supplied by the Directorate of Clothing, General Engineering and Maintenance (DCGEM). It was modified to eliminate most of the pockets.

The garment systems were tested on the instrumented mannequin using a heat flux of $80KW/m^2$ ($1.9\ cal/cm^2.s$) with a burn duration of 4.5 seconds. A summary of the relevant TPP test and mannequin testing results can be found in Tables 4 to 7 in Crown & Dale's (1992) report. Results showed that, regardless of which type of underwear was worn, the Nomex®IIIA/PBI® flightsuit provided the greatest protection, followed by the Nomex®IIIA flightsuit, and then the FR wool/Conex® (Crown & Dale, 1992).

Design Specifications and Interaction Matrix

Establishment of design specifications is the next stage in the design process. Based on the interview results, design specifications, which are listed randomly in Table 2, were developed in detail for each of five principle criteria.

An interaction matrix of design specifications was then established (TABLE 3). Some specifications in Table 2 were omitted because they are not relevant to the prototype flightsuit design (e.g., garments should have good workmanship), although they are important in the flightsuit's final production. The interaction matrix was used to illustrate a) specifications that were in direct conflict with each other, represented by **0**; b) specifications that required accommodation to be in the same design, represented by **1**; and c) specifications that created no conflict, represented by **2**.

Two pairs of specifications in the matrix were defined as in direct conflict, although the majority of pairs of specifications presented no conflict. The second specification, "cover limbs completely (with gloves & boots)," directly conflicted with No.7, "sleeve can be

TABLE 2. Design Specifications for Flightsuit Design

THERMAL PROTECTION:
- garment should cover torso completely
- garment should cover limbs completely (with gloves & boots)
- collar should provide   protection
- materials for accessories should not be destroyed by intense heat

FUNCTIONAL REQUIREMENTS

- garment system should be appropriate for both cold & hot weather (or alternatively using two different systems)
- collar should prevent chafing by shoulder straps
- in hot weather, garment should remain cool at the places least able to evaporate such as waist and underarm
- sleeve can be rolled up to cool off
- garment colour should be relatively light
- a complete range of sizes should be available
- each size should be consistent
- garment should fit at crotch
- garment should be adjustable to provide better fit
- garment should allow smooth movement and full extension of arms, etc.
- garment should provide adjustable closures for easy on/off operation
- garment should provide sufficient pockets for equipment and other needed accessories
- garment shape and fit should not be distorted by insertion of equipment into pockets
- garment with all accessories in pockets should minimize interference of user's movement
- seams/seam finishing should not detract from comfort

PSYCHOLOGICAL REQUIREMENTS
- style should have familiarity among military personnel
- colour should conform to military uniform
- appearance should look neat

PRODUCTION
- garment should present good quality in terms of workmanship
- feasible for mass production

MAINTENANCE
- garment should be of easy care
- accessories on garment (e.g. clips, zippers and pads) easy to be repaired/replaced

TABLE 3. Interaction Matrix of Garment Specifications for Flightsuit Design

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1 cover torso completely		2	2	1	2	1	2	2	2	2	1	1	1	2	2	2	2	1	1	2
2 cover limbs completely(with gloves & boots)			2	1	2	1	0	2	2	1	1	1	1	2	2	2	2	1	1	2
3 collar should provide protection				1	1	1	2	2	2	2	1	1	1	2	2	2	2	1	1	2
4 garment system should be appropriate for both cold & hot weather(or using two different systems)					1	2	2	2	2	2	2	1	1	2	2	2	2	1	1	2
5 collar should prevent from chafing by seat belt, etc.						1	2	2	2	2	2	1	1	2	2	2	2	1	1	2
6 garment should keep cool at the places least able to evaporate such as the waist & the underarm							2	2	2	2	2	1	1	2	2	2	2	1	1	2
7 sleeve can be rolled up to cool off								2	2	2	2	1	1	2	2	2	2	1	1	2
8 a complete range of sizes should be available									2	2	2	2	2	2	2	2	2	2	2	2
9 each size should be consistent										2	2	2	2	2	2	2	2	2	2	2
10 garment should fit at crotch											2	1	1	2	2	2	2	2	2	2
11 garment should be adjustable to provide better fit												2	1	2	2	2	2	1	1	2
12 garment should allow smooth movement and full extension of the arms, etc.													1	1	1	2	2	1	1	2
13 garment should provide adjustable closures for easy on/off operation														1	1	1	2	1	1	2
14 garment should provide sufficient pockets for equipments & other needed accessories															1	1	2	1	0	1
15 garment shape and fit should not be distorted by insertion of equipment and pockets																1	1	2	2	2
16 garment with all accessories in pockets should minimize interference of user's movement																	2	2	2	2
17 seams/seam finishing should not destruct comfort																		2	2	1
18 garment style should have familiarity among military personnel																			1	2
19 garment should be neat in appearance																				2
20 garment should be capable of mass production with good quality																				

0 = Conflict; 1 = Accommodation; 2 = No conflict

rolled up to cool off." The conflict was exhibited explicitly in the current flightsuit. Both current one-piece and two-piece flightsuits were designed with controlled sleeve cuffs with limited Velcro® adjustment. The pilots could not roll up their sleeves even in hot weather because of the narrow sleeve opening. This current design apparently compromised comfort to serve the purpose of protection.

Another example of design specifications in direct conflict can be seen in the relationship between No.14, "garment should provide sufficient pockets for equipment and other needed accessories," and No.19, "garment should be neat in appearance." To the researcher, having numbers of pockets on a garment would make the garment bulky and cumbersome and therefore affect the garment's appearance. However, to the aircrew members participating in the interview, to have numerous pockets on a garment does not necessarily present a conflict with neat appearance (they did not complain about the garments' appearance regarding the pockets). It could be interpreted that the pilots much prefer to have many pockets on the flightsuit rather than to compromise the pockets for nicer appearance. Therefore, the two specifications were still defined by the researcher as in direct conflict, but the specification of providing sufficient pockets was deemed to take priority over neat appearance.

Though some pairs of specifications did not show direct conflict, they required some accommodation in the design. One such example is in the relationship between No.14, "garment should provide sufficient pockets for equipment & other needed accessories," and No.12 "garment should allow smooth movement and full extension of the arms." A garment with many accessories in the pockets could somehow interfere with the wearer's movement. The design of the pockets therefore requires some accommodation to combine the two specifications, especially in the pockets' shapes and locations so that they would not obstruct smooth movements. Another example of design specifications that require accommodation is No.3, "collar should provide protection," and No.18, "garment style should have familiarity among military personnel." The collar should be designed to meet the requirements of thermal protection. Some collar styles may provide desired protection for pilots but their styles are not suitable for a military uniform. Certain accommodation is therefore needed for the collar design to make it suitable for both criteria.

Prototype Development

The design specifications for designing optimum thermal protective flightsuit systems became a guide for the next stage of the design process: prototype development. Eight different flightsuits incorporating the four parameters of interest -- garment fit (loose vs close), garment style (one-piece vs two-piece), various closure systems and seam types -- were designed using AutoCAD® and PcPattern® programs. Detailed features of each of eight garments are summarized in Table 4.

Table 4. General description of Eight Garments, Incorporating Four Parameters

Garment	Style	Fit	Closure system	Seam type
1	one piece	close	A(stand up collar, exposed front opening & zipper closure)	flat felled
2	one piece	close	B(convertible collar, hidden front opening & cuffed closure)	serged
3	one piece	loose	A(stand up collar, exposed front opening & zipper closure)	flat felled
4	one piece	loose	B(convertible collar, hidden front opening & cuffed closure)	serged
5	two piece	close	A(stand up collar, exposed front opening & zipper closure)	flat felled
6	two piece	close	B(convertible collar, hidden front opening & cuffed closure)	serged
7	two piece	loose	A(stand up collar, exposed front opening & zipper closure)	flat felled
8	two piece	loose	B(convertible collar, hidden front opening & cuffed closure)	serged

General Garment Style & Fit of Garments

The one-piece (coverall) and two-piece (shirt & pants) garment styles were adopted for the new designs, since they are the most common styles of military uniforms. Garments 1-4 were one-piece coveralls; garments 5-8 were shirts and pants.

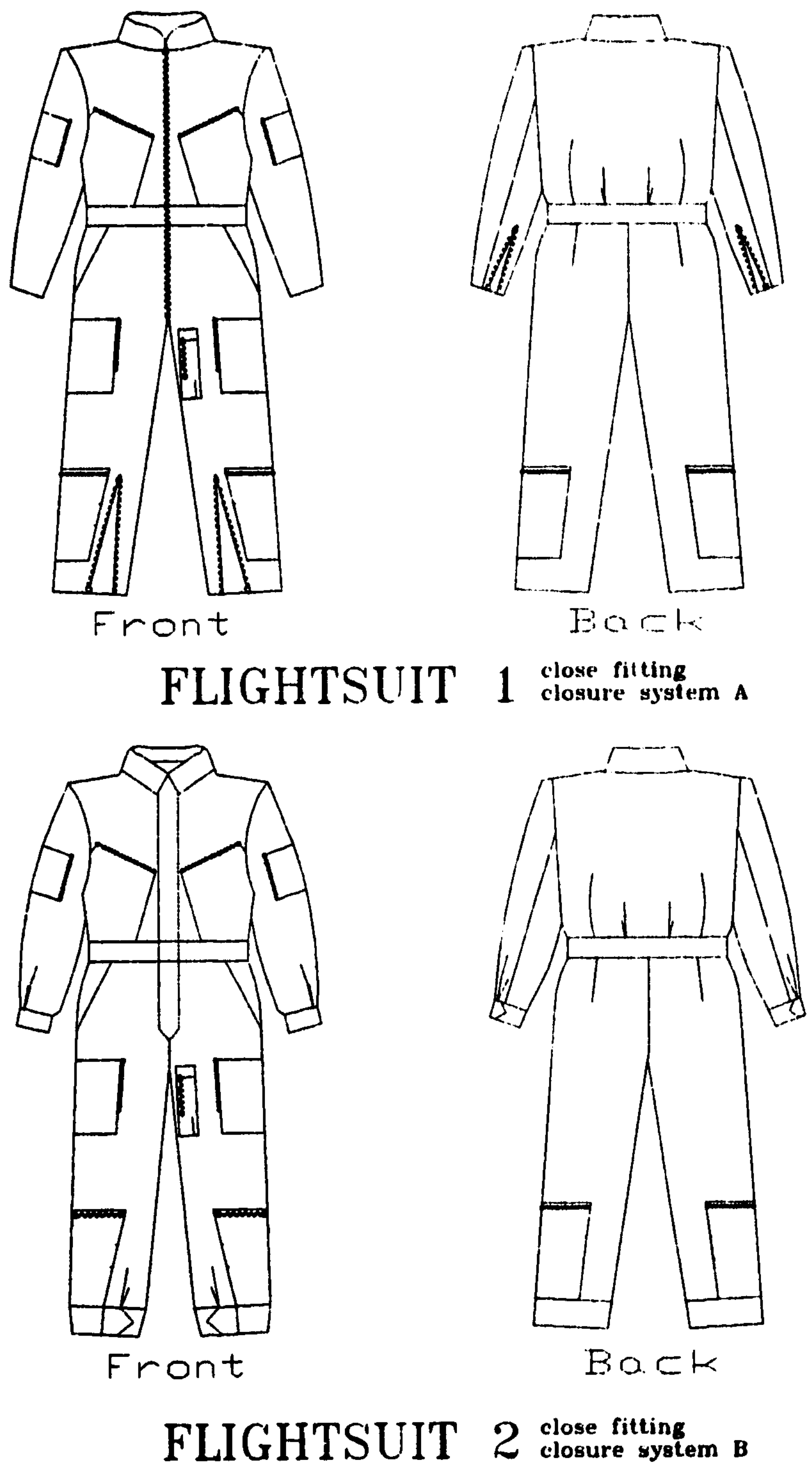
The patterns (size 42) of both current one-piece and two-piece flightsuits, including all the pockets, were digitized into a computer. With the focused interview results (Table 1) and the design specifications (Table 2) at hand, the first two new designs were developed as modifications to the current flightsuit patterns.

<u>One-piece, close fitting designs</u> (Figures 3 & 4)

The close fitting designs were made first for the coverall. The current one-piece coverall was considered as a close fitting garment. Since pilots complained that sleeves on the one-piece flightsuits were too tight to allow free movement (Table 1), and since according to the design specifications established earlier, the garment should allow smooth movement and full extension of arms (Table 2), modifications were made on the sleeves to correct the defect: armholes on both front and back bodice pattern pieces were lowered 1cm to give more room and allow full extension of arms. For garment 1, the collar, front zipper guard and sleeve & leg closures conformed to closure system A (Table 4). For garment 2, closure system B was incorporated. These design details are discussed in the following section on the <u>Closure System</u>.

<u>One-piece, loose fitting design</u> (Figures 5 & 6)

The loose fitting coveralls (garments 3 & 4) were designed by modifying the tight-fitting design patterns. Design 3 was developed from the pattern of design 1 (with closure system A), and design 4 was developed from design 2



<u>Figure 3</u>. Details of flightsuit designs 1 & 2.

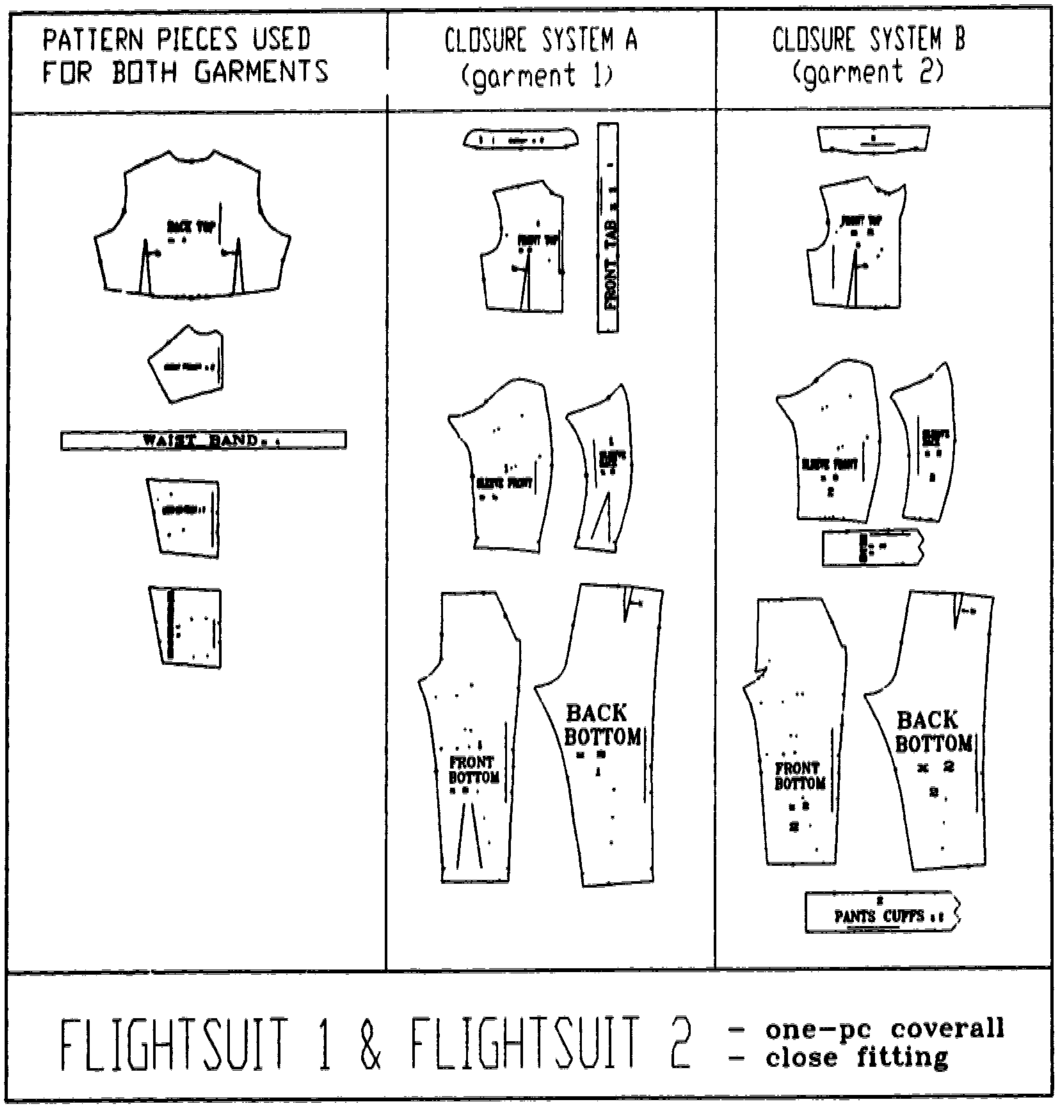
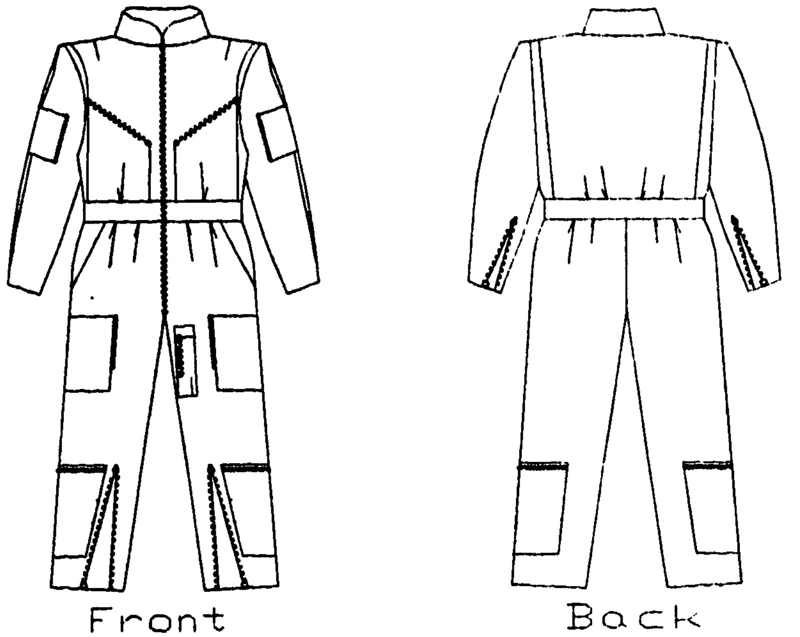
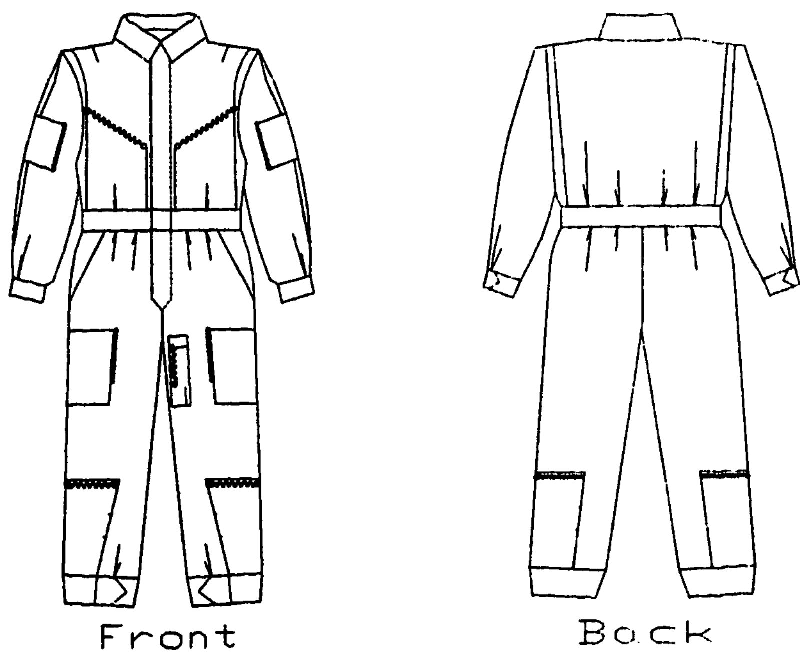


Figure 4. Major pattern pieces for flightsuits 1 & 2.



a. FLIGHTSUIT 3 loose fitting closure system A



b. FLIGHTSUIT 4 loose fitting closure system B

Figure 5. Details of flightsuit designs 3 & 4.

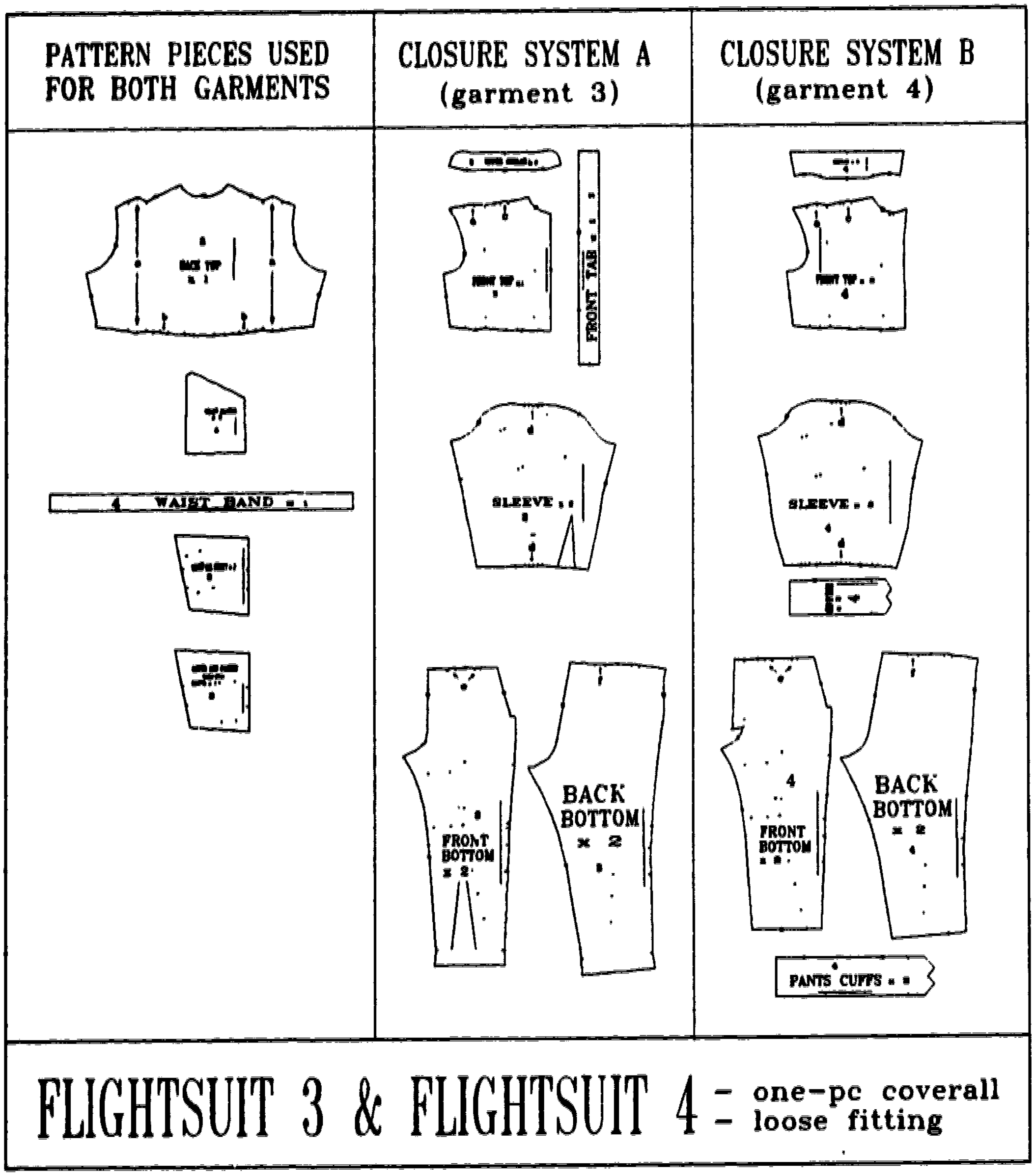


Figure 6. Major pattern pieces for flightsuits 3 & 4.

(closure system B). During the video-taping of the pilots' movement, it was observed that the shirt back was strained when pilots extend their arms forward. The garment's back, therefore, requires extra fullness for movement. Changes were made to the patterns to make the garments more loose-fitting. Two 7cm flanges were added to each of the front and back bodice of the coverall to produce a much looser garment construction, as illustrated by point "a" in Figure 6. The chest pockets were modified to fit the front flange. The original darts on the front & back bodice and back pant (point b, Figure 4) were changed to tucks (point b, Figure 6) to give the garment extra fullness. Additional 3cm tucks were added to the front shoulder (point c, figure 6). Five centimetre tucks were also added to the front pants (point e, figure 6) and 4cm tucks to the back pants around the body's waist (point f, figure 6). The two-piece sleeve was replaced by one-piece sleeve since it provides a looser structure. The pattern was designed by adapting the sleeve sloper in the PcPattern®. One 7cm flange, point "d" in figure 6, was added to the centre of each sleeve to make it roomier.

<u>Two-piece, close-fitting design</u> (Figures 7 & 8)

Since there were many complaints about the fit of the current two-piece flightsuit (Table 1), the patterns for the tight fitting two-piece garments (garments 5 & 6) were

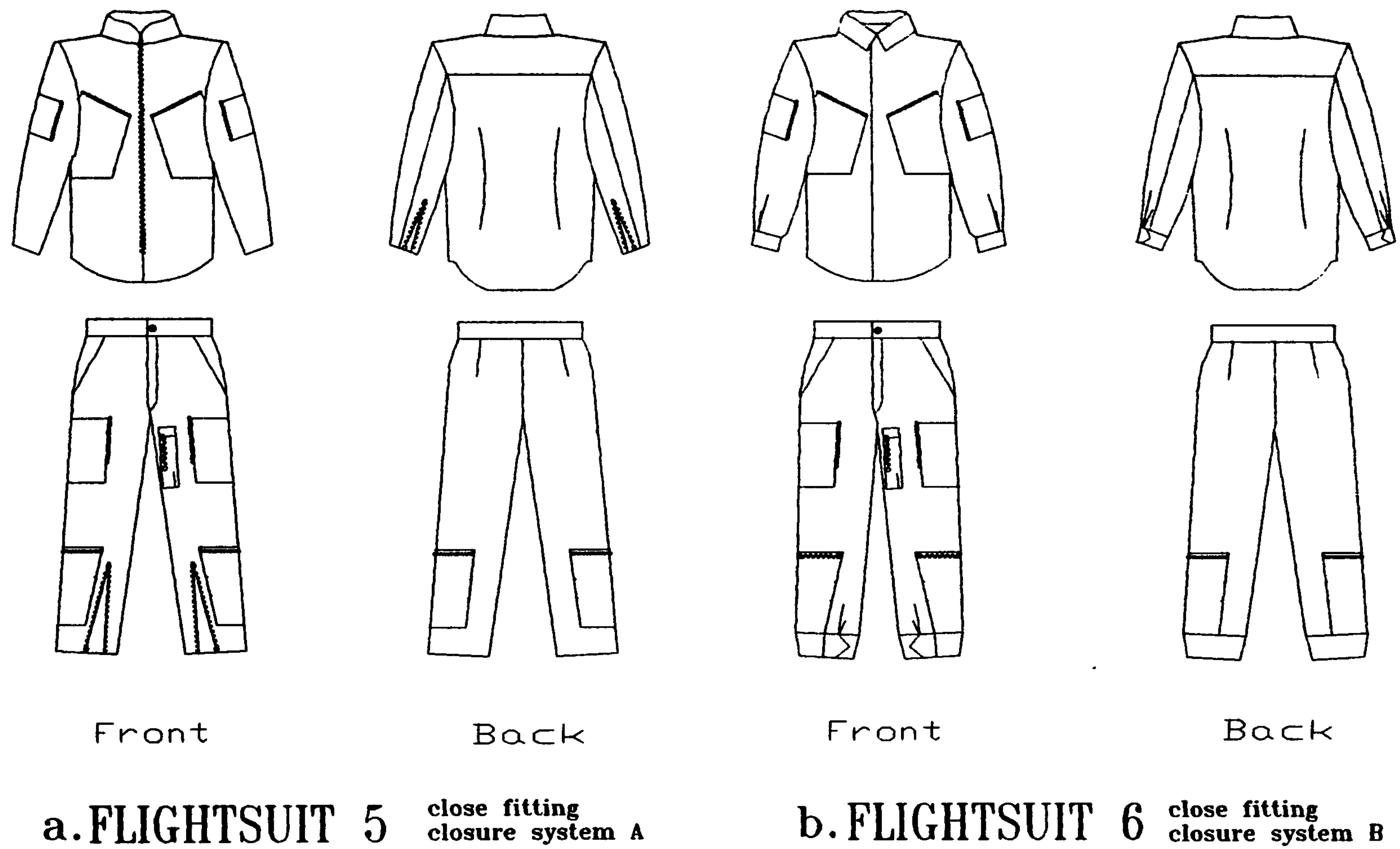


Figure 7. Details of flightsuit designs 5 & 6.

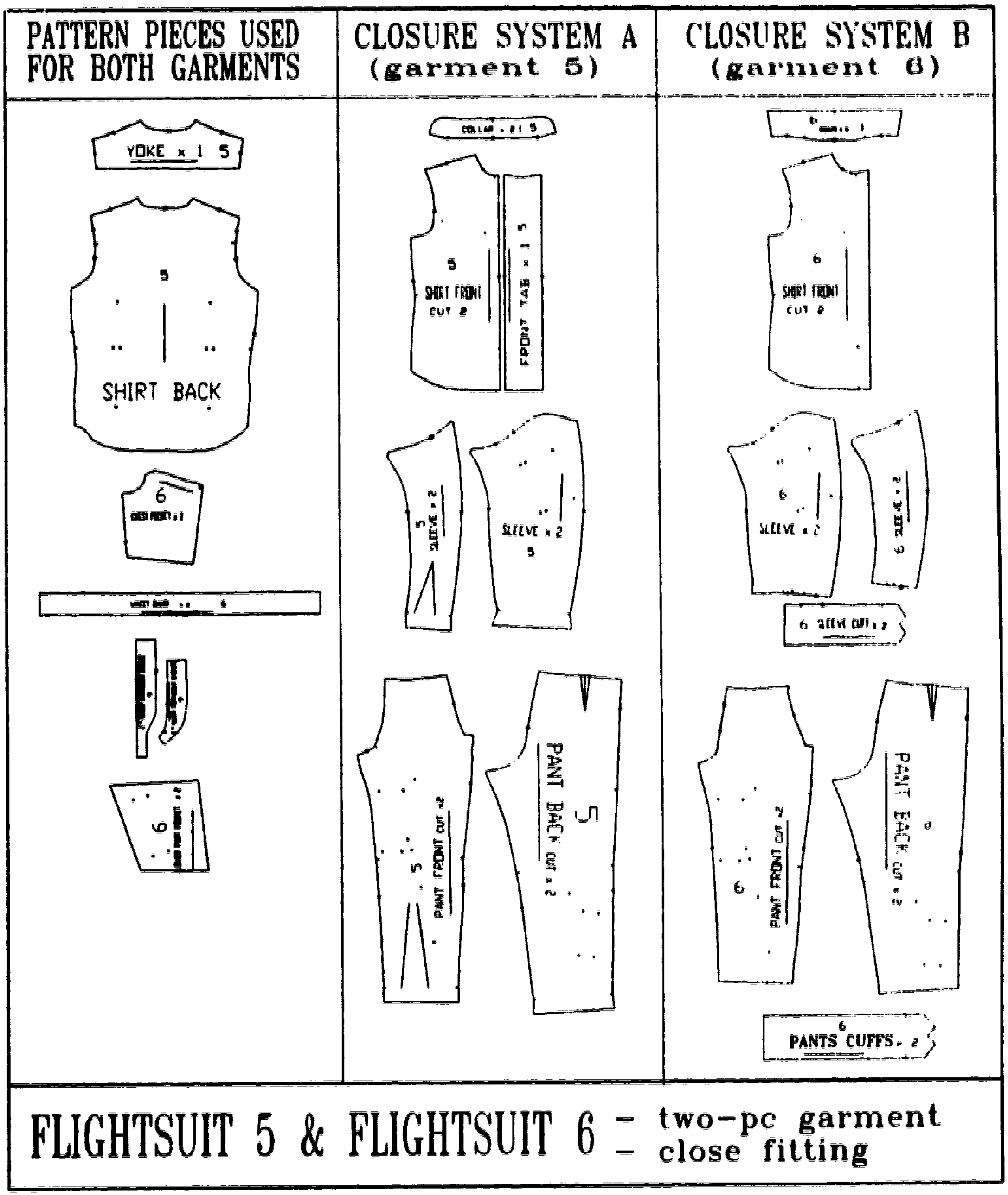


Figure 8. Major pattern pieces for flightsuits 5 & 6.

developed by adapting the sloper pattern for the men's shirt and pants (size 42) from the PcPattern® program. Modifications were made on the sloper patterns according to the design specifications. This style was much tighter than the current two-piece garment: the modified pattern was 2.5 cm narrower at the underarm on each side (a to b, Figure 9) than the current garment, and the shirt length was 5 cm shorter than the current one (Figure 9). The pilots also complained that the pant's crotch is too deep (Table 1). The experimental pant's crotch was made 5 cm shorter to correct the defect. The pants have Velcro® adjustments at each side to help hold up the pants. As in the one-piece garment design, the armhole was lowered to provide more arm movement. The sleeves were lengthened 2cm in order to cover the arms completely when pilots stretch them.

<u>Two-piece, loose fitting design</u> (Figure 10 & 11)

The designs for the loose-fitting two-piece garments (garments 7 & 8) were developed by modifying the close-fitting designs 5 & 6 with the corresponding closure system. Two 6cm flanges were added to the shirt back below the yoke (a'in figure 11). Unlike the one-piece design, no flange was added to the shirt front because the flange at the front would open and look awkward without control at the waist. The shirt's front chest was enlarged by stretching out 1.5 cm at each side of the underarm (b' in figure 11). A 3cm tuck, point "c'" in figure 11, was also added to the front

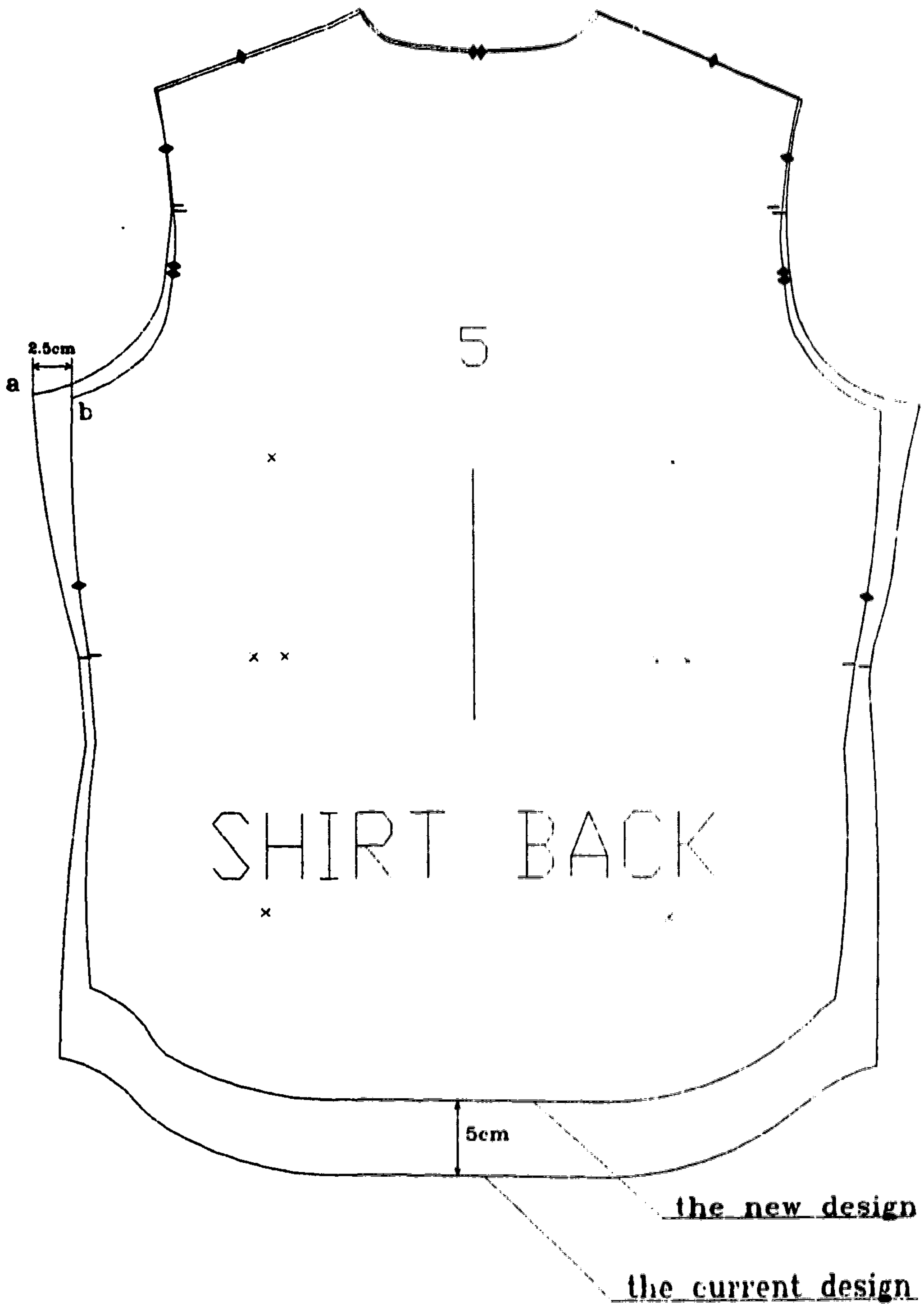
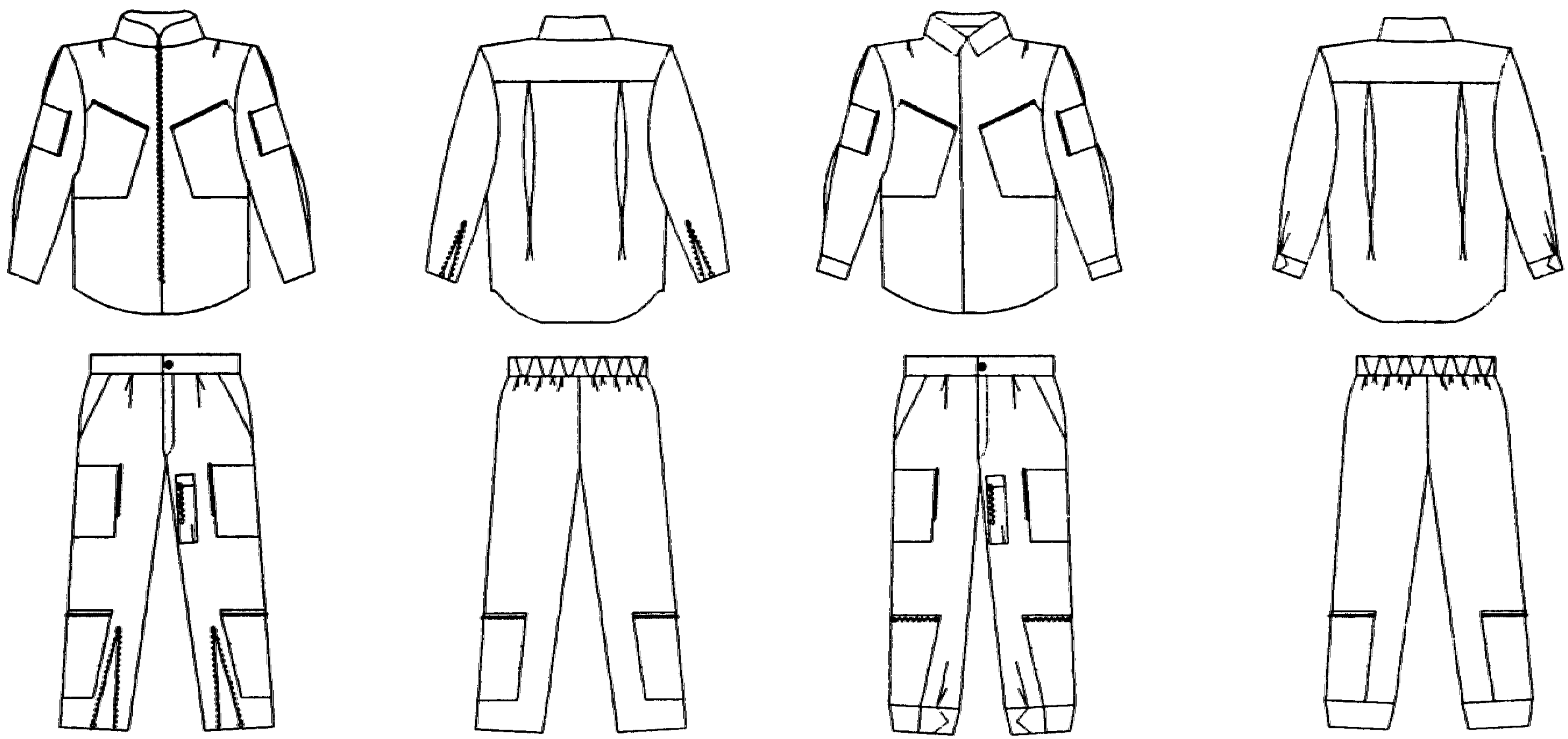


Figure 9. Comparison of the current & the experimental 2-pc close-fitting shirt back.



Front — Back — Front — Back

a. FLIGHTSUIT 7 loose fitting closure system A

b. FLIGHTSUIT 8 loose fitting closure system B

Figure 10. Details of flightsuit designs 7 & 8.

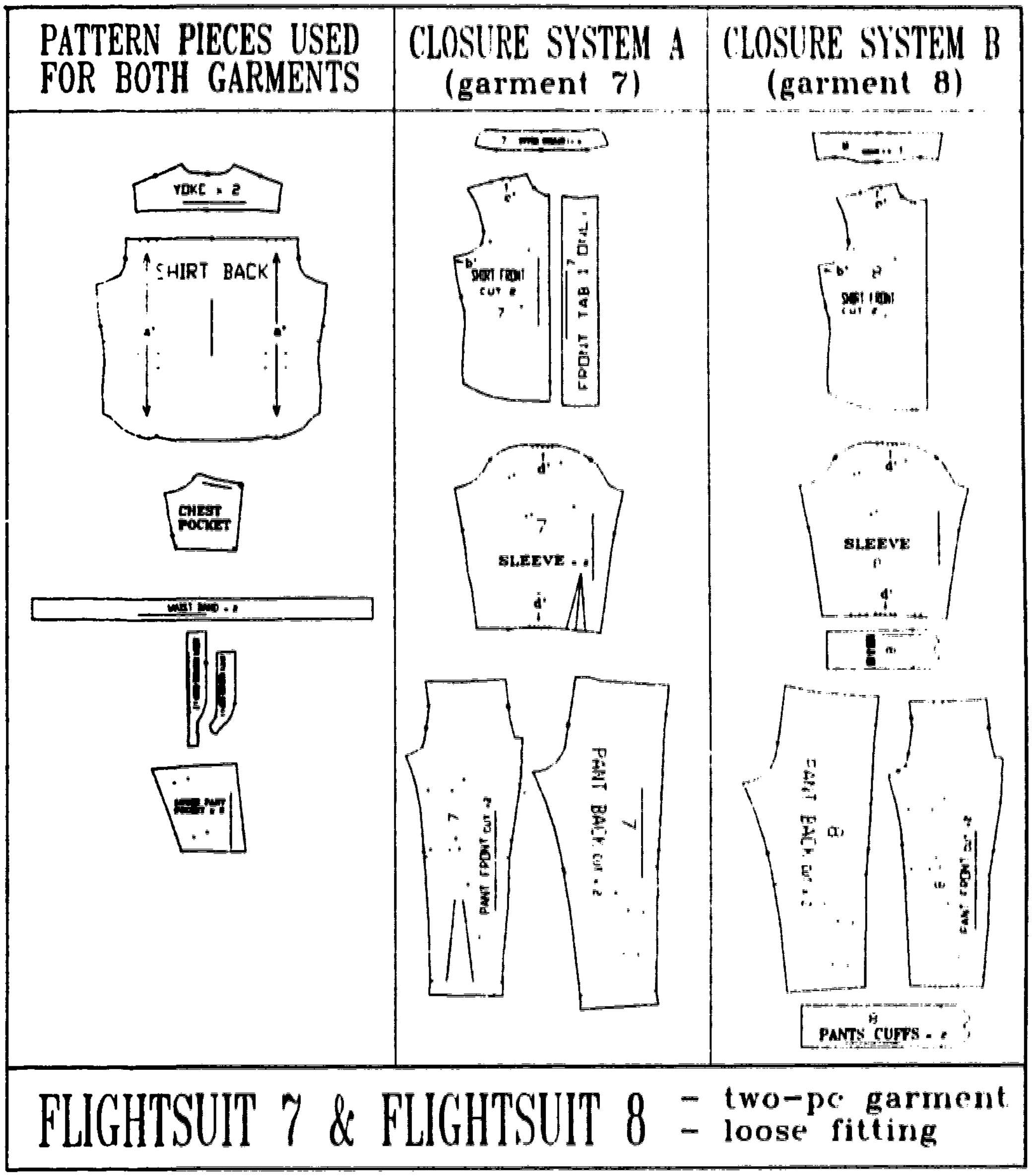


Figure 11. Major pattern pieces for flightsuits 7 & 8.

shoulder to give more ease. The loose sleeves were designed with a 7cm flange added to the centre of each sleeve (d' in figure 11) that was modified from the sloper in the PcPattern®. To give the garment more fullness, the pants were designed with elasticized waists. The loose pants also have Velcro® adjustments at each side to keep the pants tight.

Closure Systems

The closure system is a special concern regarding a garment's thermal protection. The closure systems for the flightsuits include the elements of collar, front opening, and sleeve & pant leg opening. Both current flightsuits have convertible collars and exposed front zipper openings, with cuffed closure on sleeves and zippered closure on pant legs. In the experimental designs, there were two closure alternatives. Closure system A comprised a stand-up collar, an exposed front zipper with a zipper guard underneath, and zippered closure on sleeves and pants. Closure system B comprised a modified convertible collar, a hidden front zipper, and cuffs with Velcro® closure on the sleeves and pants.

Collars

The current regular convertible collar does not provide desired thermal protection, since it is too floppy and flat. It lies on the shoulder and leaves the neck exposed to fire in case of fire accident. Moreover, pilots were not satisfied with their current collar because of its discomfort. It gets in the way when pilots wear shoulder harnesses during flight (Table 1). According to the design specifications established for the research (Table 2), the collar should provide sufficient thermal protection for the neck. In the experimental designs, therefore, it was determined to have a stand-up collar as an alternative to the convertible collar, the former expected to give better protection for the neck area and to prevent chafing by the shoulder harnesses. This collar was used in garments 1,3,5 & 7.

The other collar option was a modification of the current convertible collar. It was designed with a more curved neckline which fits better around the neck, and enables the collar to stand more vertically, giving better protection than the one on the current flightsuits. A comparison of the current and the new convertible collar is demonstrated in Figure 12. This modified collar was used in garments 2,4,6 & 8.

Front Opening

The current flightsuits have exposed zipper openings with zipper guards underneath. This closure was kept as one choice for the front-opening design, and was used in closure system A (garments 1,3,5 & 7). Another alternative, a hidden zipper, was used in closure system B (garments 2,4,6 & 8). For the two-piece garments, the front openings differed only

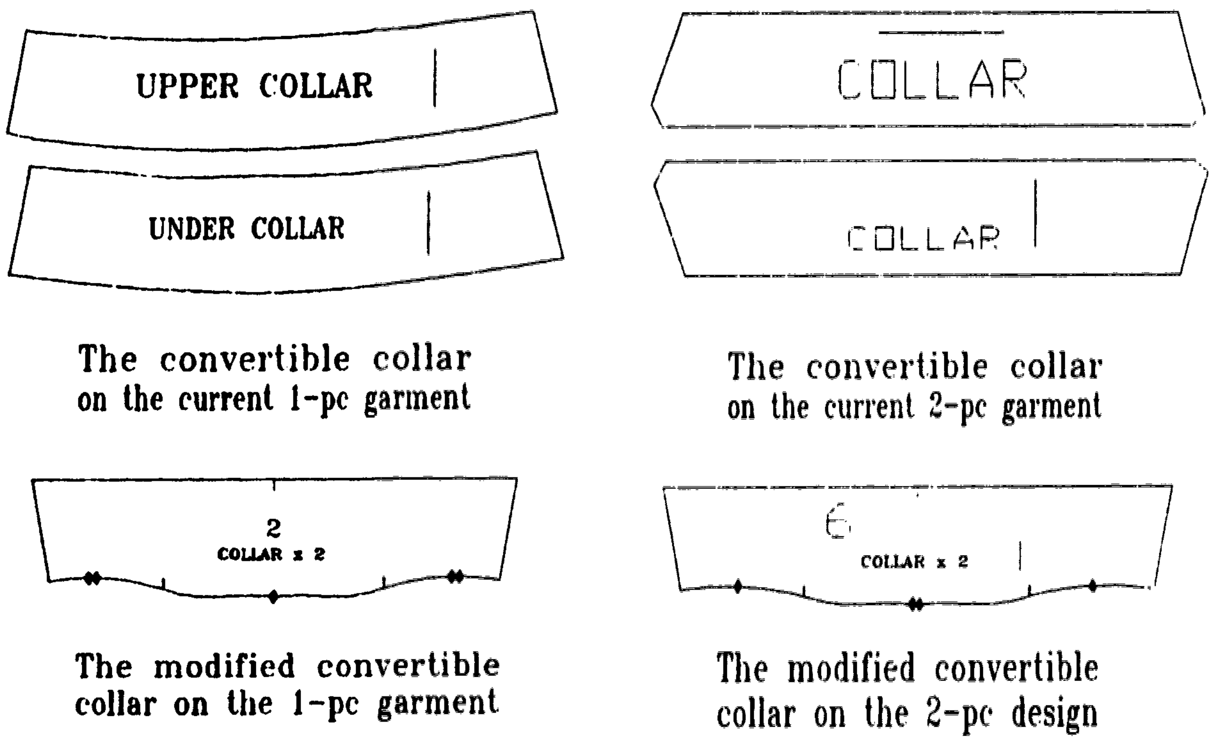


Figure 12. Comparison of the current & the modified convertible collar.

on the shirts. The different front openings are shown in Figure 3.

Closure System on Sleeves & Legs

Two closure options were chosen for the sleeves & legs: cuffed closures and zippered closures. Consideration was given to garment comfort when the zipper closure was designed to replace the current cuffed closure on the sleeves. A major complaint about current flightsuits was that the sleeves were designed with a controlled cuff-Velcro® closure, which can allow only a limited Velcro® adjustment and cannot be rolled up because of the narrow cuff opening. The intent of this design was to provide wearers with maximum protection by keeping their arms covered. However, the design resulted in poor thermal comfort since pilots cannot roll up their sleeves even when working outside of the plane in summer.

A zippered sleeve closure, like the one currently used on the legs, was considered as one alternative which could remedy this deficiency and was used for closure system A. The zippered opening allows pilots to open and push up the sleeves to cool off in hot weather (Appendix 5). The zippered leg closure on the current flightsuits was unchanged for closure system A.

In closure system B, the current cuffed sleeve closure was preserved. The same type of cuffed closure was used on the legs. To allow more free movement of the arms, the sleeves with the cuffed closures (closure system B) were made 2cm longer than the original length.

Seam Type

Flat felled seams (as on the current flightsuits) were chosen as one option to compare with regular serged seams on garments. Flat felled seams were used on garments 1,3,5 & 7, and the regular serged seam on garments 2,4,6 & 8.

Other Important Features in the Flightsuit Design

According to the requirements of pilots, one pocket was added to the right sleeve. To accommodate the flanges on the sleeves of the loose designs, the sleeve pockets were raised to the top of the sleeves (garments 3, 4, 7 & 8). One pocket was also added to the upper right leg to meet the pilots' demands. This design provides flexibility for wearers by allowing for scribble pads and/or clips. The clips are clipped onto both of the upper leg pockets. If pilots need scribble pads, they can put them into the pocket. The lower leg pockets were raised 2cm to avoid their current problem of being too low to reach. On the two-piece garment, the pant's back pockets were omitted because they add thickness and were considered useless.

All eight patterns were based on size 42 to fit a size 40 mannequin with some ease. These designs were then sewn into muslin prototypes. The muslin prototypes were tried on a mannequin of the same size (size 40) as the one to be used in the mannequin testing. Some corrections were made to have the garments fit better and make the donning and doffing operations easier on the mannequin. After changes and corrections were made, the patterns and markers of each design were sent to a local manufacturer for the production of flightsuits for thermally instrumented mannequin testing.

In the first round of mannequin testing, the fabric selected for the flightsuits was 203g, twill weave Nomex® IIIA. This fabric performed well in the TPP test and the mannequin testing during the material analysis stage, but the researcher believed that it would not perform so well that it would fail to differentiate thermal protective properties among garment designs.

Prototype Evaluation

Since user evaluation of fit, mobility, comfort and other related aspects are both complicated and time consuming, they will be conducted in later phases of the project and are considered to be outside the scope of this thesis. The evaluation of the designs for this thesis focus only on mannequin testing. The procedure for evaluation is outlined in Chapter 4.

CHAPTER 4

PROTOTYPE EVALUATION

Prototype evaluation is the final stage of, and an element indivisible from, the **functional apparel design process**. This chapter emphasizes evaluation of the thermal protection provided by the eight flightsuits through discussion of the mannequin testing results. As discussed in the literature review in Chapter 2, the best method to evaluate the thermal protection offered by garments is to determine the potential for skin damage through a simulated accident. This can be done by using a thermally instrumented mannequin and a simulated flash fire exposure system. The evaluation of the flightsuits' thermal protection consisted of both quantitative measurements and qualitative evaluation.

Design criteria and specifications were established early in the research (Table 2). The thermal protective property of the flightsuits was evaluated against the specifications under thermal protection in order to determine whether the garment designs met these criteria.

Experimental Design

The flightsuit designs incorporated the four parameters that DREO (Defence Research Establishment Ottawa) requested. Those included garment style (one-piece or two-piece), garment fit, closure system and seam type. The effect of each variable on the garment's thermal protection could be tested while controlling for the other variables. With four parameters for the design and two variations for each parameter, the total number of designs would be sixteen (2^4). However, since it was expected that seam type would have little effect on a garment's thermal protection in mannequin testing, seam type varied with closure systems (flat felled seam with closure system A, regular seam with closure system B) reducing the total to eight garment types.

Three replications of each garment type were tested on the mannequin. Since testing would be destructive, an additional replication of each garment was produced as a sample. Garments were tested on the mannequin without underwear in order to better differenciate the effects of garment design parameters.

To remove residual mill finishes prior to the mannequin testing, garments were laundered once in accordance with CAN/CGSB-4.2 No.58, procedure IIID (50°C wash, moderate mechanical action, synthetic detergent, line dried).

The Mannequin and the Exposure System

The research used the mannequin exposure system built at the University of Alberta. The system is described by Dale, Crown, Ackerman, Leung & Rigakis (1992). The mannequin was moulded from an existing male store mannequin. Appendix 3 shows front and rear views of the completed mannequin and sensor areas on the mannequin. The energy absorbed by the mannequin surface is measured by one hundred and ten skin simulant heat flux sensors, which adequately cover the mannequin except at the wrist, hands and feet.

Flash fires are generated with propane diffusion flames by six identical burner assemblies which are controlled by a computer system. Average heat fluxes from 67 to 84 kW/m^2 (1.6 to 2 $cal/cm^2.s$) with burn durations of 3 to 4.5 seconds have been obtained reliably with the system. A computer controlled data acquisition system is used to run the test, record and store the data, calculate the extent and nature of the skin damage and display the results. The sampling rate of the system is 800 Hz.

The mannequin and the flash firing system are housed in a special concrete block room with remote controlled dampers to the outside for a fresh air supply during firing and venting. A viewing window is located in the wall that separates the firing room from the main laboratory building.

Test Procedure

The first round of mannequin testing was completed May 25th-27th, 1993. An average heat flux of 75.0 kW/m^2 and an exposure time of 3.5 sec were selected to provide desired simulation of flash fires in a postcrash accident that an aviator could confront. A video camera recorded the firing process through the viewing window. Before each exposure, the operator keyed information such as the burn duration and the total sampling time into the computer system. Once all sensors were cooled to 25°C or lower and the sensors displayed on the unit were satisfactory, the operator gave a run signal to start burning. The video camera was also started to record each garment burning process.

During the testing, factors such as ignition, afterflame, combustion products and the areas where severe thermal shrinkage occurred were recorded as observations. Other factors such as the thermal integrity of the garments were summarized after the mannequin testing through the videotape analysis and observation of burned garment samples and photographs.

A nude mannequin test was completed at the beginning and end of each replication in order to examine the stability of testing conditions and to assess the maximum possible burn damage for the selected exposure condition. During testing, some sensors failed to work (Table 5), and as a consequence, the maximum possible total burn percentage recorded during these tests was lower than the desired maximum possible burn damage.

One full replication of all garment designs was tested each day to minimize possible experimental error resulting from varying test conditions (e.g., equipment bias, temperature, humidity, etc.).

The thermal protective quality of a garment can be judged from estimates of the extent of skin damage. For this

TABLE 5. Summary of the First Round of Mannequin Testing Results

Garment / Replication	% Mannequin Reaching Burn Criteria			Observations
	2nd	3rd	total	
1-pc, close-fitting,				Very brief afterflame.
closure system A				Velcro tabs at back
1.1	29.8	7.0	36.8[a]	waist opened & melted.
1.2	28.6	7.8	36.4[b]	lots shrinkage, some
1.3	27.1	7.0	34.1[b]	colour change and
Design 1 mean & st'd dev.			35.8±1.5	brittleness
1-pc, close-fitting,				Very brief afterflame.
closure system B				serious shrinkage.
2.1	21.4	8.0	29.7[a]	Velcro tabs at back
2.2	20.4	8.8	29.2[b]	melted and opened. Some
2.3	25.4	7.7	33.0[b]	colour change and
Design 2 mean & st'd dev.			30.6±2.1	brittleness.
1-pc, loose-fitting,				Very brief afterflame.
closure system A				Serious shrinkage. Loss
3.1	29.2	7.7	36.8[a]	of ease & fullness.
3.2	27.6	7.7	35.3[b]	Velcro tabs at waist
3.3	30.0	7.0	37.0[b]	melted and open. Some colour
Design 3 mean & st'd dev.			36.3±0.9	change & brittleness
1-pc, loose-fitting,				Very brief afterflame.
closure system B				Serious shrinkage. Loss
4.1	25.8	7.7	33.4[a]	of ease & fullness. Velcro
4.2	24.0	7.7	31.6[b]	tabs at waist melted
4.3	26.3	7.7	34.0[b]	& opened. Some colour
Design 4 mean & st'd dev.			33.0±1.2	change & brittleness.
2-pc, close-fitting, closure system A				No afterflame. Serious
5.1	26.4	7.7	34.0[a]	shrinkage removed the
5.2	22.5	7.7	30.2[b]	garment ease. Pants do
5.3	22.1	7.7	29.8[b]	not fit at front
Design 5 mean & st'd dev.			31.3±2.3	waistline.
2-pc, close-fitting, closure system B				Very brief afterflame.
6.1	21.4	8.8	30.2[a]	Serious shrinkage to
6.2	20.4	8.3	28.7[b]	the body. Shirt shrunk
6.3	23.6	8.3	31.9[b]	tight to the back. Colour
Design 6 mean & st'd dev.			30.2±1.6	change & brittleness
2-pc, loose-fitting,				Very brief afterflame.
closure system A				Serious shrinkage. Lose
7.1	23.9	8.3	32.2[a]	of ease & fullness.
7.2	24.2	9.1	33.3[b]	Outer folds of loose
7.3	22.3	8.3	31.2[b]	fabric melted. Some colour
Design 7 mean & st'd dev.			32.2±1.1	change & brittleness
2-pc, loose-fitting, closure system B				Very brief afterflame.
8.1	21.0	7.7	28.7[a]	Serious shrinkage
8.2	21.1	8.5	29.6[b]	removed garment ease &
8.3	21.9	8.3	30.2[b]	fullness. Some colour
Design 8 mean & st'd dev.			29.5±0.8	change & brittleness.

[a] Maximum total burn possible = 82.7 (6 sensors not working)
[b] Maximum total burn possible = 82.2 (7 sensors not working)

worse is of importance. Through the computer-controlled data acquisition system, quantitative measurements such as the area and percentage of second and third degree burns on the skin were calculated and recorded. Computer printouts of the mannequin with front and rear view illustrated the location and degree of skin damage. Other information such as test identification, a summary of sensor response and a graph of cumulative burns were also provided. A typical computer printout for each garment design is shown in Appendix 6.

The length of the inside leg was measured both before and after exposure to evaluate the garments' thermal shrinkage. The left leg (with pants) was chained during the burning to hold the mannequin in place, a procedure which greatly reduced shrinkage. The thermal shrinkage of the garments was therefore only based on the length of the right inseam.

The burned garments were saved for later qualitative evaluation. Pictures were taken to reveal changes on different seam types. The results for the eight designs were compared to determine variations in thermal protection among the different garment designs and provide useful information for further design changes and corrections.

Though the thermal protective quality of various seam types could be evaluated by small scale testing, it was evaluated here qualitatively. The seams on the exposed garments were examined for brittleness and colour change.

Results: First Round Mannequin Testing

The results of the first round of mannequin testing are summarized in Table 5. The average percentage of mannequin surface reaching 2nd & 3rd degree burn was calculated for each design, and the observations were recorded. The data were grouped according to the design parameters (Table 6). A three way analysis of variance was used to test for differences among the designs. Since there were no significant interaction effects, only the main effects of

TABLE 6. Comparison of Skin Burn Damage by Flightsuit Design Parameter

Design:	1	2	3	4	5	6	7	8
Average Total Burn (%)	35.8	30.6	36.3	33.0	31.3	30.2	32.2	29.5

one-pc garment mean burn (design 1 to 4) 33.9%	**two-pc garment mean burn** (design 5 to 8) 30.8%
loose fit mean burn (design 3,4,7,8) 32.8%	**close fit mean burn** (design 1,2,5,6) 32.0%
closure system A, flat fell seam - mean burn (designs 1,3,5,7) 33.9%	**closure system B, serged seam - mean burn** (designs 2,4,6,8) 30.8%

the design criteria are described. The ANOVA results (Table 7) indicate that there are significant differences of protection among the designs varying on both garment style and closure system, but not among those which vary on garment fit. The Null hypothesis is therefore rejected for the effects of both garment style and closure system.

TABLE 7. Analysis of Variance: Effect of Garment Parameters on Extent of Skin Burn Damage

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	119.126	3	39.709	17.039	.000
STYLE	58.750	1	58.750	25.209	.000
EASE	3.488	1	3.488	1.497	.239
CLOSURE	56.888	1	56.888	24.410	.000
2-Way Interactions	11.397	3	3.799	1.630	.222
STYLE EASE	3.046	1	3.046	1.307	.270
STYLE CLOSURE	8.343	1	8.343	3.580	.077
EASE CLOSURE	0.008	1	0.008	0.004	.953
3-Way Interactions	4.550	1	4.550	1.952	.181
STYLE EASE CLOSURE	4.550	1	4.550	1.952	.181
Explained	135.073	7	19.296	8.280	.000
Residual	37.288	16	2.331		
Total	172.362	23	7.494		

Garment style - one-piece vs two-piece

The one-piece garments present significantly higher percentage of skin burn damage on the mannequin surface than the two-piece garments which had been worn on the mannequin with the shirt tucked into the pants. The average mannequin surface reaching 2nd & 3rd degree burn for the one-piece garments is approximately 3% higher than those for the two-piece garments (Table 6). Since the garments were designed with basically the same pockets and accessories, and were sewn from the same fabric, it is likely that the difference results from the double layering of shirts & pants in the lower torso area. This can be seen by comparing the computerized illustration of the burn injury patterns (Appendix 6). From the front view of the mannequin, it can be seen that all the one-piece garments had some second degree burn in the lower torso, but no burn damage showed in the area for the two-piece garments except a small 2nd degree burn on one replication of design 8. The area of burn damage on the rear view is also much smaller for the two-piece garments than for the one-piece garments. Tucking the shirts into the pants during testing added both a garment layer and an extra air layer between the outer garment and skin. These factors reduced the convection heat transfer to the mannequin and therefore lessened burn damage on its surface.

Garment fit - loose vs close

In the first round of mannequin testing, the garment fit showed no significant effect on thermal protection (Table 7), with the difference in percent total burn between the two design groups (loose vs close-fitting garments) being less than 1% (Table 6). This outcome was unexpected since a controlled looseness of garments had been expected to be an important factor contributing to thermal protection. It was observed during the burning that some areas on the loose-fitting garments shrank, especially in areas with extra ease and fullness such as chest, back and around the waist. Thus, most of the garment ease from the loose fitting style was removed with shrinkage. The primary cause for this occurrence was speculated to be the fabric's thermal shrinkage. To test this explanation, a second round of testing was conducted using a lower shrinkage fabric and is discussed later in this chapter.

Closure system

Closure system B exhibited significantly greater protection overall than system A (Tables 6 & 7). The average mannequin surface reaching 2nd and 3rd degree burn criteria for the garments with closure system A is 33.9%, while with system B it is 30.8%. Three elements possibly contributed to the effect of closure system on the garments' thermal protection - collar design, front opening, and closure system on sleeves and legs.

Sleeve & leg closures

The cuffed closure on sleeves and legs contributes the most to the results. Thermal shrinkage at the right inseam (Appendix 7) on the garments with cuffs is over 27% less than the ones with zippers. Cuff closures hold sleeves and legs in place better than the zipper-closure system during exposure. They prevented fore-arms and lower legs from being exposed to the fire from garment thermal shrinkage. In addition, they keep sleeve and leg openings more secure and reserve more isolated air space between the garments and the body, which helps to reduce the convection heat transfered to the skin. The computer printouts of skin burn patterns (Appendix 6) support the latter explanation as they demonstrate that effect of the closure system was beneficial to the whole limb rather than just the wrist and ankle regions.

Collar

Although the overall protective performance of closure system B is better than that of closure system A, the convertible collar included in system B did not contribute to the result. The computer data print-outs showed that the neck area suffered higher degree of burn damage with the convertible collar than with the stand-up collar. The depth of burn damage (cm) was recorded by four sensors located in the neck area: neck back, neck right side, neck left side and neck front. The average burn depth (cm) in each location was calculated for each design, and the total burn damage around the neck was defined as the sum of the average burn depth in these four locations (Table 8). The total burn for the convertible collar (design #2,4,6,8) is about 23% more than that for the stand-up collar (design #1,3,5,7). Figure 13 illustrates the comparison of thermal damage suffered around the neck with the two collar designs. In three out of four cases, the convertible collars have deeper burn depth than the stand-up collars. Data in Table 8 show that severe burn damage occurring at the left side and the front of the neck contributed the most to the results for the poor protection offered by the convertible collars. This outcome results from the collar construction -- the stand-up collar has a more erect shape and closer fit than the convertible collar, giving better protection around the neck.

TABLE 8. Depth of Burn Damage (cm) around the Neck in Different Collar Designs

	NECK BACK	NECK RIGHT	NECK LEFT	NECK FRONT	TOTAL BURN (sum B.R.L & F)
Stand-up Collar					
garment 1	0.0668	0.0000	0.0488	0.0580	0.1736
garment 3	0.0689	0.0000	0.1207	0.1725	0.3621
garment 5	0.0000	0.0000	0.0610	0.2080	0.2690
garment 7	0.0027	0.0326	0.1661	0.2080	0.4094
AVERAGE	0.0346	0.0082	0.0992	0.1616	0.3035
Convertible Collar					
garment 2	0.0554	0.0000	0.1387	0.2080	0.4021
garment 4	0.0335	0.0000	0.1488	0.2080	0.3903
garment 6	0.0000	0.0000	0.2080	0.2080	0.4160
garment 8	0.0000	0.0000	0.1648	0.2080	0.3718
AVERAGE	0.0222	0.0000	0.1651	0.2080	0.3951

One apparent weakness in the stand-up collar, however, was that the two ends of the collar did not meet at the centre front because of the presence of the zipper. This

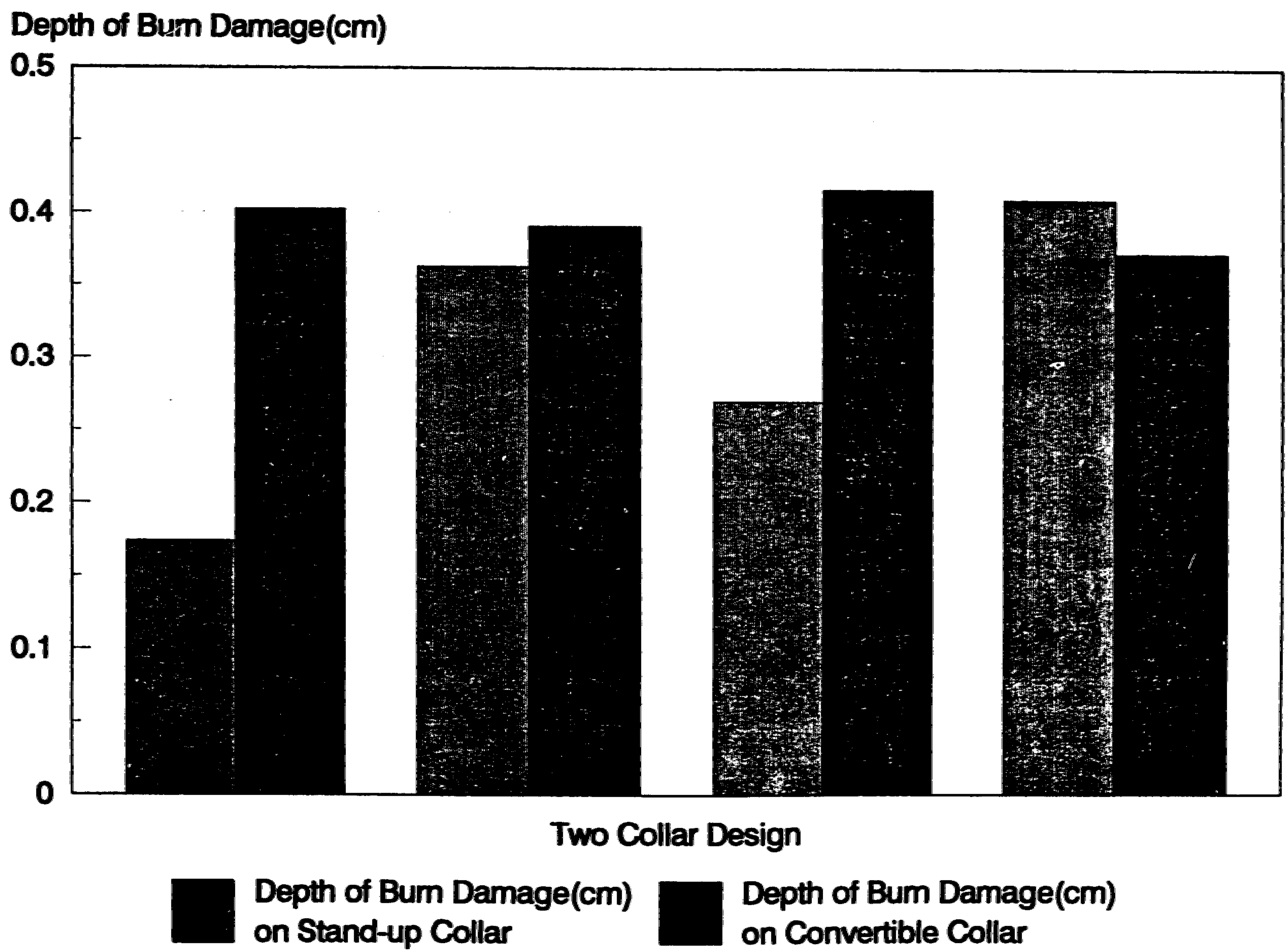


FIGURE 13. COMPARISON OF TWO COLLAR DESIGN

left the centre front neck unprotected. This defect was rectified in a later design modification

Front opening

The exposed-zipper front opening (closure system A) presents little difference in protection from the covered-zipper front opening (closure system B). On the computer data printouts, the data recorded by the sensors at the locations of chest centre, abdomen upper centre and abdomen lower centre showed no burn for all eight garments.

Seam type

Flat felled seams and regular seams were included as two alternatives in the prototypes. Since the different seam types showed no obvious effect on extent of skin burn in the mannequin testing, this element was evaluated qualitatively. Photographs were taken both before and after exposure to reveal any changes in the seams in the most exposed areas, such as the outside leg seam. From exposed garment specimens and photographs taken following testing, the two seam types appear to present little difference (Appendix 8).

The Second Round of Mannequin Testing

Since thermal shrinkage occurred in the first round of mannequin testing and masked any effect of garment fit, a second round was conducted to reveal the influence of garment fit on thermal protection. To avoid the problem of thermal shrinkage, a 65% FR viscose/35% aramid fabric ($290 g/m^2$) was chosen for the flightsuits since it is known to exhibit less thermal shrinkage than the Nomex® IIIA used in the first round. Based on the results from the first round of testing, the flightsuits were modified to combine the better features of the first eight designs. The two-piece garment style (shirt & pants) was selected because of its better performance in the last experiment. As stated above, closure system B presented better quality of thermal protection except the convertible collar. In the new designs, therefore, the closure system combined the cuff & Velcro® closure on sleeves and pant legs, the front opening with exposed zipper, and a modified stand up collar with the two ends overlapping at centre front. This combination was expected to provide better thermal protection over the previous designs. A regular serged seam was chosen for easy production.

With the two-piece style and the revised closure system, garment No.9 was designed as a close fitting flightsuit, and No.10 as a loose fitting flightsuit. Garments were sewn up without pocket zippers and prepared prior to testing as for the first round. They were laundered once before testing, using the same laundry procedure (CAN/CGSB-4.2 No.58, procedure IIID). Three replications of the two modified designs were tested.

The results of the second round, including t-test results, are given in Table 9. The mean percentage of mannequin surface reaching burn criteria for the close-fitting garment 9 is significantly greater than for the loose-fitting garment 10. This result illustrates the difference that failed to show in the first round of testing. Photographs taken both before and after burning show that the fabric did not shrink seriously as happened

TABLE 9. Second Round of Mannequin Test Results

Garment/ Replication	% 2nd Degree Burn	% 3rd Degree Burn	% Total Burn Damage
9.1	15.1	7.0	22.1
9.2	16.7	7.0	23.7
9.3	14.9	5.5	20.4
Design 9: mean & st'd dev.			$22.1^{a} \pm 1.65$
10.1	12.1	7.0	19.1
10.2	8.5	7.0	15.5
10.3	8.1	7.0	15.1
Design10: mean & st'd dev			$16.6^{a} \pm 2.20$

[a] $t=3.46 > $ critical value of $t=2.78$ ($p<0.025$)

in the first round, and the ease and fullness from the loose construction design were well reserved (Appendix 9). These test results demonstrate that loose-fitting garments can provide better thermal protection than the close-fitting garments. Thus, the hypothesis of no difference in thermal protection between loose-fitting & close-fitting garments is rejected.

CHAPTER 5

SUMMARY, CONCLUSIONS & RECOMMENDATIONS

The purpose of this study was to follow a functional design process in the development and evaluation of thermal protective flightsuits for use by Canadian Forces flight personnel. Fire hazard has been one of the most severe dangers faced by military personnel, especially pilots, as a result of the nature of their work. Flightsuits should protect pilots from severe burns in fire accidents and extend their escape time from fire. The flightsuits that pilots are currently wearing do not provide the thermal protection required by their working environment, and they do not meet all the functional needs of pilots.

The framework of the research was adopted from Orlando's (1979) Functional Design Process. This design process allows the designer to follow a strategy-controlled procedure to incorporate various design parameters into the final design. A literature review carried out in an early stage of the research included aspects such as test methods for thermal protection, heat transfer, mechanism of skin burn, review of previous field accidents involving pilots, thermal protective fabrics & garments, flightsuit design and the design process. A focused group interview was conducted at CFB Edmonton to collect subjective data from users regarding their needs and the suitability of previous and current flightsuits. Their typical activities and movements in and around their planes was recorded on video tape.

The experimental designs incorporated four parameters requested by Defence Research Establishment Ottawa: style, fit, closure system and seam type. With 1-piece and 2-piece styles, close fitting and loose fitting constructions, two closure systems and two seam types (which varied with closure system), a total of eight different flightsuits (Table 4) were designed using AutoCAD® and PcPattern® programs.

The new one-piece close-fitting garments were designed by adapting the current one-piece flightsuit. Corrections were made to give the sleeves more freedom for arms movements, and more pockets were added to meet the pilots' needs. Garment 1 was designed with closure system A, and garment 2 with closure system B (Table 4). The one-piece loose-fitting garments were designed based on the close-fitting patterns with the correspondent closure system. Flanges were added to both front and back bodice and to the sleeves. The darts on the bodice front, back and pants were changed to tucks for more ease. These give the garments controlled ease. Extra fullness was also added on the chest, the shoulder, the back and the pants. The pockets were modified to accommodate the loose-fitting style.

Because the current two-piece garment does not fit well, the experimental designs for the two-piece close-fitting garments were adapted from the slopers of men's shirt and pants in the PcPattern® programme. Changes were made to accommodate arm movement and better fit. Some pockets were added or relocated to correct the defects on the current flightsuits. Garment 5 was designed with closure system A, and garment 6 with closure system B. Like the one-piece garments, the two-piece loose-fitting garments were based on the close-fitting designs. Flanges were added to the shirts' back below the yoke and to the sleeves. The front chest was enlarged. Tucks were used instead of darts to produce the controlled loose-fitting garments. More ease was added to the shoulder and the pants. Sleeve pockets were relocated to accommodate the loose-fitting construction.

The thermally instrumented mannequin built at The University of Alberta was used to evaluate the thermal protection of the flightsuits. Three replications of each garment style were produced in Nomex®IIIA and tested. The parameters of garment style and closure system had significant effects on the flightsuits' thermal protection. The two-piece flightsuits provided significantly greater protection than the one-piece ones. This result is thought to be mainly due to the double layering of garments in the lower torso area.

Cuffed closures on the sleeves and the legs offered greater protection than zippered closures by holding the sleeves and legs in place better, preventing the skin from being exposed to fire due to garment shrinkage and by reducing air movement inside the garment. The stand-up collar provided better protection than the convertible collar, because of its erect shape which fits better around the neck and covers more of the neck than the convertible collar.

Neither front closure type nor seam type had any noticeable effect on the garments' thermal protection. The first round of testing also failed to differentiate between close-fitting garments and loose-fitting garments, due to the severe shrinkage which occurred during the testing. In a second round of testing, with lower shrinkage 65/35 FR viscose/aramid fabric, the loose-fitting garments showed significantly greater protection than the close-fitting ones, demonstrating that the parameter of garment fit can perform an important role in a garment's thermal protection.

CONCLUSIONS

The Functional Design Process has been a valuable approach to the design and evaluation of the thermal protective flightsuits in this study. It led the designer to combine the various design elements into the final designs.

The focused group interview conducted in the research provided valuable information regarding flight personnel's requirements and suitability of their previous and current flightsuits. The data collected were not only important to the designer in perceiving the design structure of this research, but will also be useful for the evaluation and further development of flightsuits.

The two-piece garments offer greater protection than the one-piece garments. Because of the double layering of shirt and pants in the lower torso area, the two-piece garments add both a fabric layer and an air layer between the outer garment and skin. These reduce convective heat transferred to the skin and therefore provide better protection than the one-piece garments.

Loose-fitting garments give higher protection than the close-fitting garments, providing the fullness is controlled and thermal shrinkage does not occur. The loose-fitting construction gives the garments extra fullness and ease which reserves more air space between the garments and the skin, and therefore, reduces the heat transferred through the garments.

Cuffed closures provide better protection than zippered closures. With the modified stand-up collar combined with an exposed front opening and cuffed closures on sleeves and pant legs, the revised closure system can provide desired protective performance.

The two seam types have little effect on the garments' thermal protection in mannequin testing.

RECOMMENDATIONS

(a) For flightsuit design and fabrication

1. This study has demonstrated that a two-piece loose-fitting garment with a closure system that comprises a fully covered stand-up collar and cuffed closures on sleeves & pant legs should provide adequate thermal protection for flight personnel when worn with appropriate underwear.

2. In the selection of fabrics for flightsuits, factors such as the fabrics' thermal protective quality, thermal comfort, properties of easy care, and colour familiarity among military uniform should be considered.

3. During the focused group interview, it was noted that the one-piece flightsuit is preferable in its overall performance to the two-piece garments. Consideration therefore should be given to pilots' preference.

4. There were special concerns expressed during the focused group interview regarding the inadequate size range available for flightsuits. A sufficient range of sizes should be available to accommodate most of the user population.

(b) For further design refinement

1. The protective performance of the one-piece flightsuit can be enhanced by having double layer constructions in some areas that are most likely to be exposed to fire, such as using double layered yoke at back shoulder.

2. The sleeve pockets should be relocated so that they will not cause discomfort for arm movement.

(c) For further research

1. This study focused only on the evaluation of thermal protection using a thermally instrumented mannequin. Further user evaluation of fit, mobility, comfort and other related aspects should be conducted through controlled exercises and field wear trials. Following such trials, further design refinement might be necessary.

2. This study has designed and evaluated the thermal protective flightsuits for males only. Women in the Canadian Forces do not have flightsuits for their gender and have expressed this concern. Future researchers therefore should take this into consideration and try to address the needs of female pilots as well.

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APPENDIX 1

Recruitment Notice & Consent Form for Focused Group Interview

University of Alberta
Edmonton
Canada T6G 2M8

Faculty of Home Economics
Office of the Dean
110 Home Economics Building, Telephone (403) 492-3883
FAX (403) 492-4821

RECRUITMENT NOTICE

To: **CANADIAN FORCES TRANSPORT PILOTS**

We are seeking volunteers to participate in a group interview relating to protective flightsuits. We want to find out through this discussion what is important to you in evaluating flightsuits for pilots. Your comments will help us meet our long-term goal of designing optimally functional flightsuits. This is part of a project funded by Defence Research Establishment Ottawa. The group interview is scheduled for **October 1, 1992** at **1:30 p.m.** and will take place in the **435 Squadron Briefing Room**. Your participation is entirely voluntary and you would be free to leave the group at any time.

If you are willing to participate, please complete and return the form below to **Major Stenberg**.

Thank you for your cooperation.

Sincerely,

Betty Crown, PhD, PHEc
Professor and Dean

YES, I am willing to participate in the group interview about protective flightsuits.

NAME: (please print): ______________________________

SIGNATURE: ______________________________________

University of Alberta
Edmonton
Canada T6G 2M8

Faculty of Home Economics
Office of the Dean
110 Home Economics Building, Telephone (403) 492-3883
FAX (403) 492-4821

Design and Evaluation of Flight Suits for Canadian Forces Personnel

INVESTIGATOR(S): Dr. B. Crown and Ms. Jackline Tan

INFORMATION ABOUT INTERVIEW PROCEDURE:

The purpose of the group interview is to determine what is important to you in the design and evaluation of flight suits. Your comments will help us meet our overall objective of designing more effective, functional clothing systems for pilots. The group interview should take approximately one hour. Your name will not be associated in any way with the data obtained. Because your participation is entirely voluntary you are free to leave the group at any time. If you have questions about the procedures you may ask them before the interview begins or at any time throughout the interview.

CONSENT:

I acknowledge that the research procedures described above and of which I have a copy have been explained to me, and that any questions that I have asked have been answered to my satisfaction. In addition, I know that I may contact the person designated on this form, if I have further questions either now or in the future. I have been informed of the alternatives to participation in this study. I have been assured that all records relating to this study will be kept confidential and that my name will in no way be associated with the data. I understand that I am free to withdraw from the study at any time without jeopardy to myself.

____
(Name)

The person who may be contacted about the research is:

Dr. Betty Crown
492-3883

____
(Signature of Participant)

____
(Name)

____
(Signature of Witness)

____
(Date)

____
(Signature of Investigator or Designee)

APPENDIX 2

Focused Group Interview Protocol

FOCUSED GROUP INTERVIEWS
ON PROTECTIVE FLIGHT APPAREL

Group: ______________________________________ Date: ____________________

Base (Location): ______________________________________

A. If applicable, instruct participants to sit in groups according to type of flight suits currently worn (for ease of recording responses).

B. Today, we are going to focus on current and past flight suits, your likes and dislikes. First, I will ask you each to take a few minutes to independently write down several things for me. I will ask you each in turn to tell me what you have written. Then we will have an opportunity to discuss your responses. Finally, I will ask you some specific questions about garment design.

1. First, focus on your current flight suits. Write down at least three things that you really like about it. What is good about it?

2. Then, please write down at least three things you do not like about it.

3. Now, focus on your last flight suit. Again, please write down at least three things you liked about it.

4. Then, write down at least three things you do not like about it.

C. O.K. Now in turn, I would like each of you to tell me what you have written.

1. What you like about the current suit.

2. What you do not like about the current suit.

3. What you liked about your last suit.

4. What you disliked about your last suit.

D. Discussion

1. a) One of the factors mentioned by many of you seems to be:

____.

Tell me more about this. What does this term mean to you? What all does the concept include? Why is it so important to you?

b) Do you think you could rate various flight suits on this criterion? How (type of descriptors)?

2. a) Another factor mentioned quite often was:

____.

Tell me more about this one too. What does it mean? Why is it so important?

b) Do you think you could rate various flight suits on this criterion? How (what descriptors)?

3. None/few of you mentioned ____.
Is this criterion not important to you, or if it is can you think why it was not mentioned (often)? (e.g. most protective clothing similar in this respect; just did not think about it).

4. What other factors should we consider in designing thermal protective flight suits?

E. Now, let us focus on some specific aspects of garment design.

1. Please describe in details what you like or dislike about the following garment features:

Collar:

Sleeves:

Cuffs:

Pockets:

Seams:

2. Do you prefer:

Looser - Closer Fitting Clothes?

Longer Sleeves - Shorter Sleeves?

Wider Sleeves - Narrower Sleeves?

Looser Cuffs - Tighter Cuffs?

Looser Waist - Tighter Waist?

One Piece Garment - Two Piece Garment?

3. Do you feel that your current suit interferes with your movement when you are working? If "yes", please specify.

4. Is the flight suit easily caught on hooks, other equipment, etc.?

5. Is it easy to put it on and take it off?

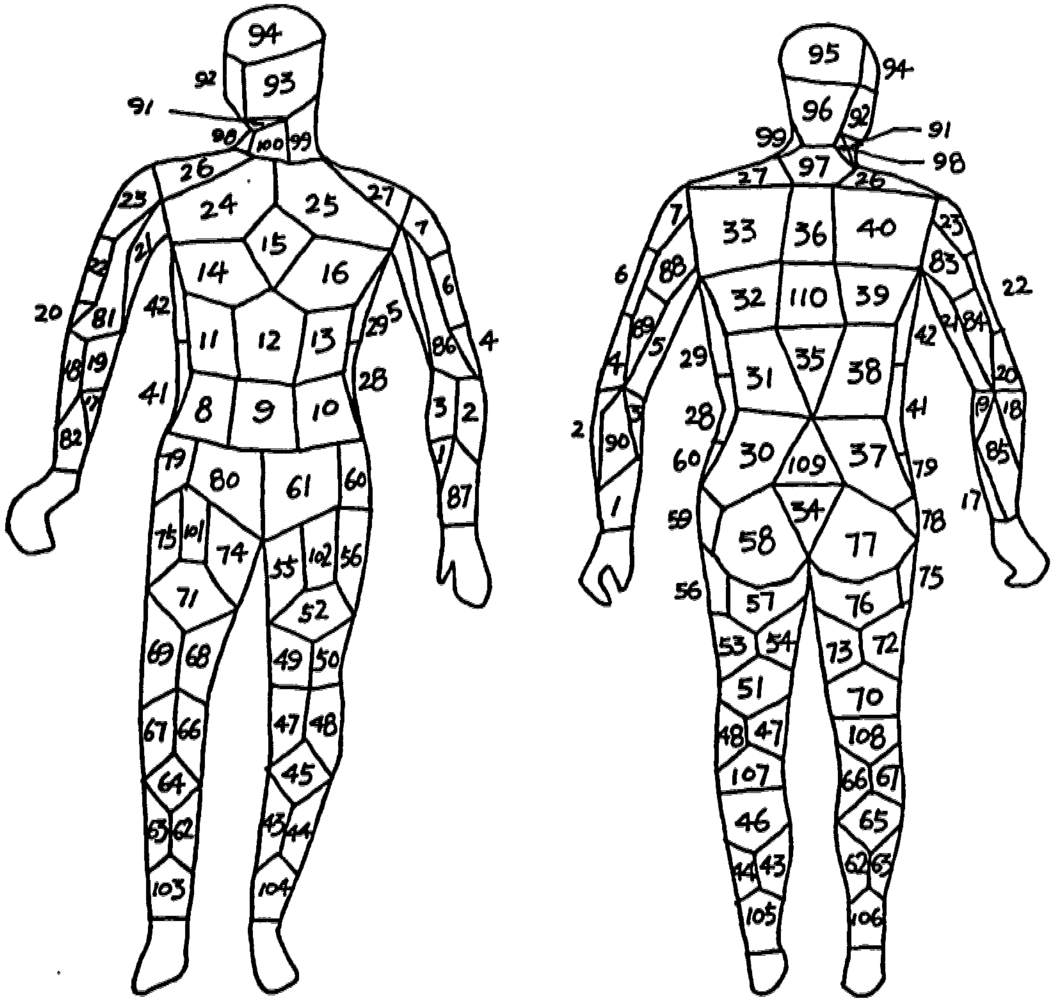
6. Does it fit with your other equipment and accessories such as helmets, gloves, parachute belts, etc.?

7. Do you feel satisfied about the overall fit of this garment?

F. Record participants' experience with accidents while wearing flight suit.

APPENDIX 3

Sensor Areas on Instrumented Mannequin



Sensor Areas on Instrumented Mannequin

APPENDIX 4

Photographs of the Selected Flightsuit Designs

Photographs were taken out due to poor copy quality

(Page 117: Design 1. One-piece, close-fitting, closure system A;
Design 4. One-piece, loose-fitting, closure system B.
Page 118: Design 6. Two-piece, close-fitting, closure system B;
Design 7. Two-piece, loose-fitting, closure system A)

APPENDIX 5

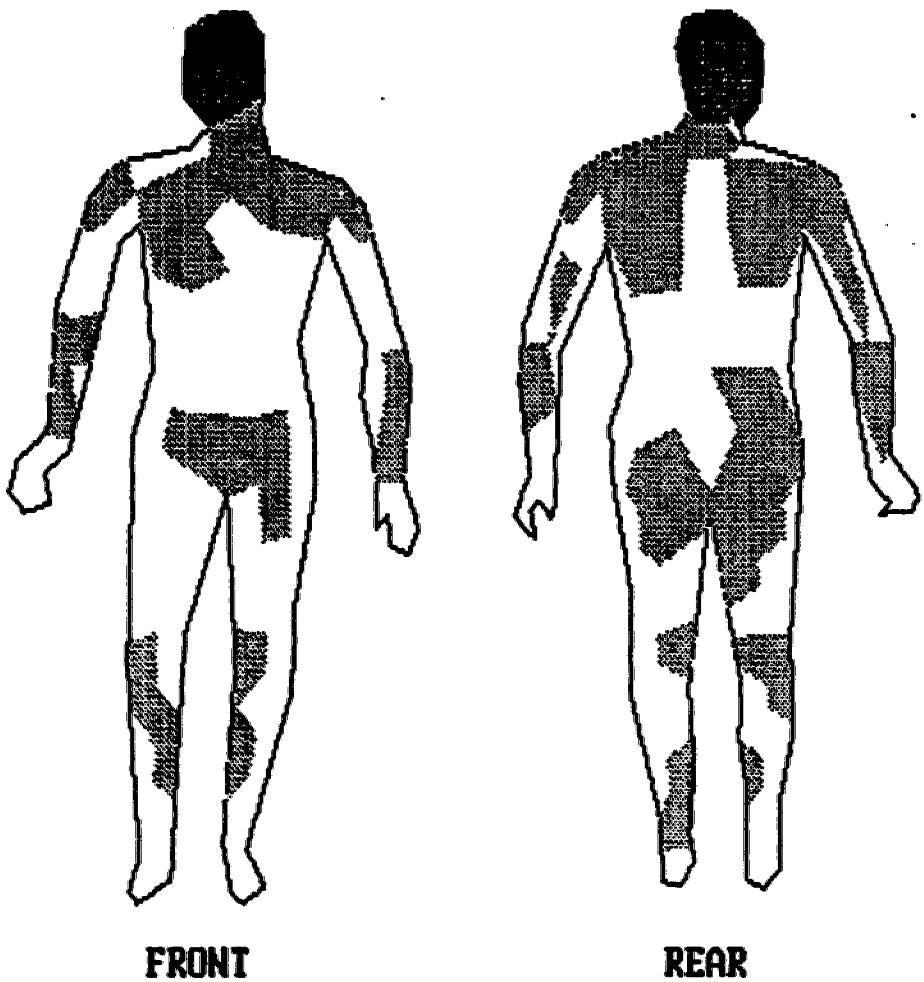
Photographs of the Cuffed Sleeve Closure and the Zippered Sleeve Closure

Photographs were taken out due to poor copy quality

(Page 120: photographs of cuffed closure & zippered closure)

APPENDIX 6

Computer Printouts from the Mannequin Testing

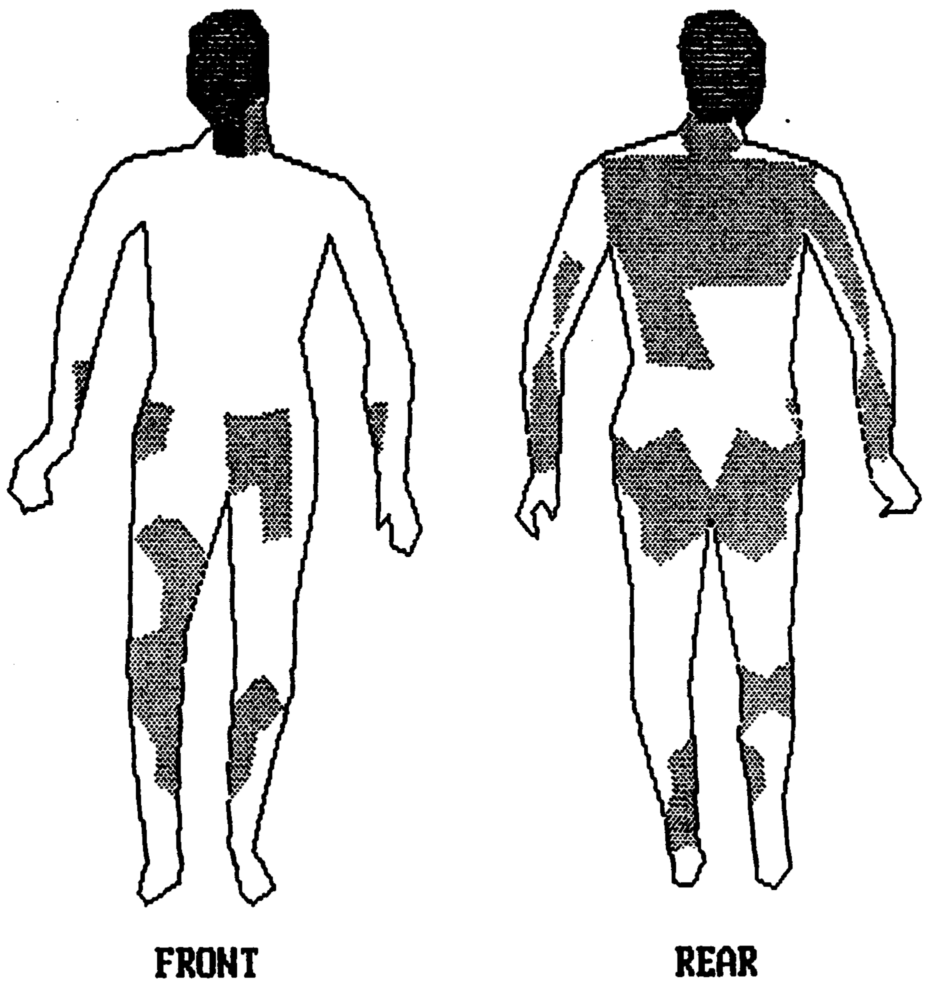


THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

Fire Protective Clothing
Evaluation System

05-25-1993
1.1 Aramid Coverall - TSZF
203 g/sq.m

Exposure	75.0 kW/m2
Exposure Time	3.5 sec
Time of Plot	60.0 sec
2nd Deg Burn	29.80%
3rd Deg Burn	7.00%
TOTAL BURN	36.80%

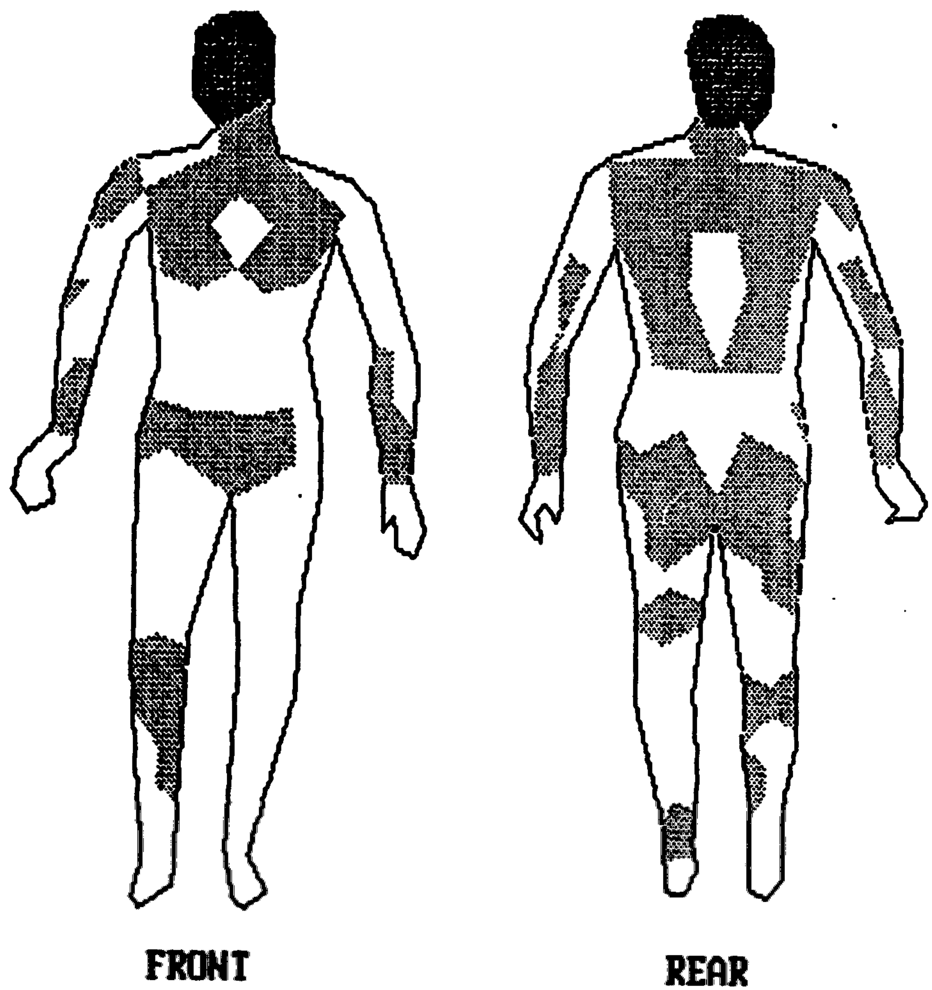


THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

Fire Protective Clothing
Evaluation System

05-27-1993
2.3 Aramid Coverall - TRCS
203 g/sq.m

Exposure	75.0 kW/m2
Exposure Time	3.5 sec
Time of Plot	60.0 sec
2nd Deg Burn	25.35%
3rd Deg Burn	7.65%
TOTAL BURN	33.00%



THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

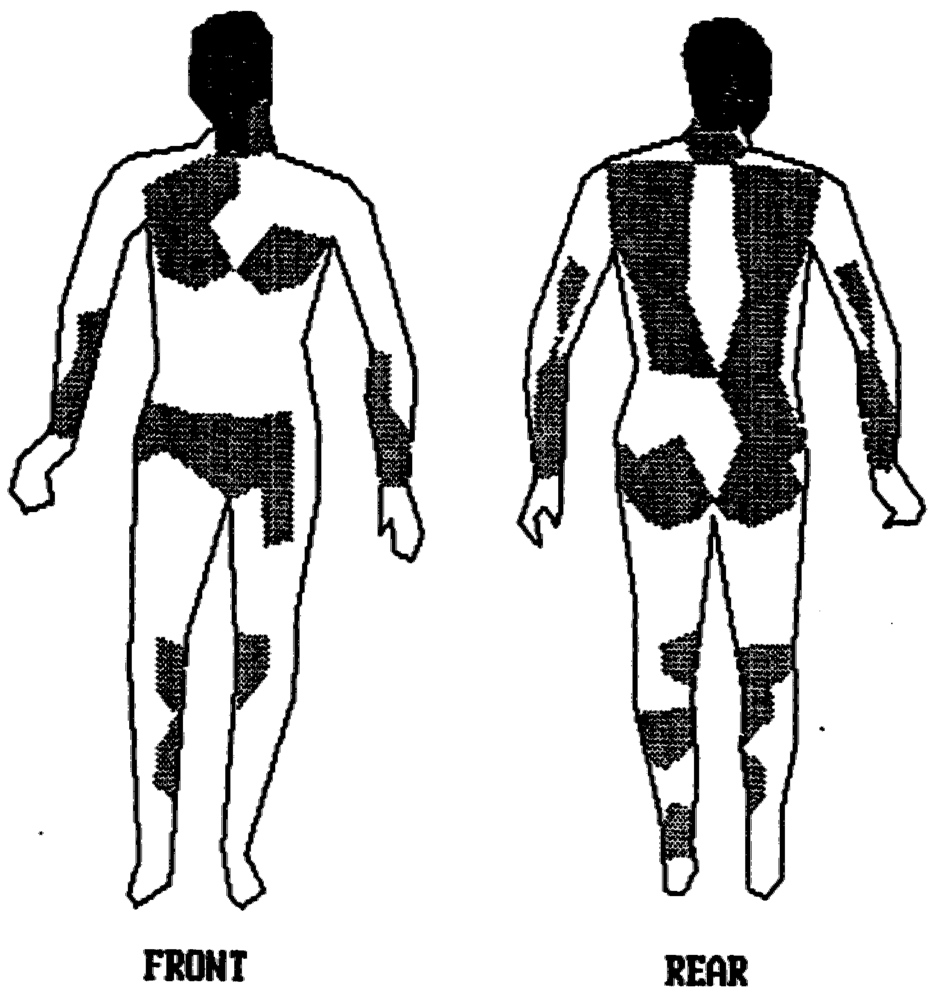
Fire Protective Clothing
Evaluation System

05-27-1993
3.3 Aramid Coverall - LSZF
203 g/sq.m

Exposure 75.0 kW/m2
Exposure Time 3.5 sec
Time of Plot 60.0 sec

2nd Deg Burn 29.95%
3rd Deg Burn 7.00%

TOTAL BURN 36.95%



THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

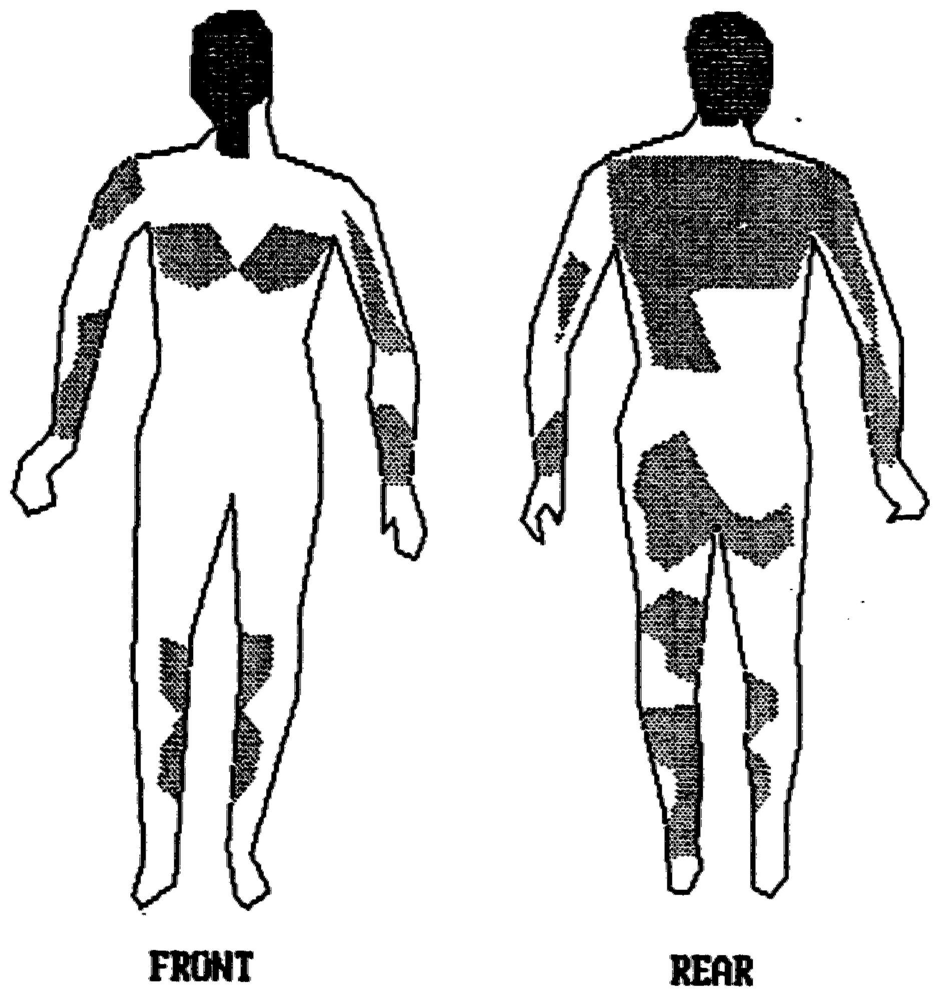
Fire Protective Clothing
Evaluation System

05-25-1993
4.1 Aramid Coverall - LRCS
203 g/sq.m

Exposure 75.0 kW/m2
Exposure Time 2.5 sec
Time of Plot 60.0 sec

2nd Deg Burn 25.75%
3rd Deg Burn 7.65%

TOTAL BURN 33.40%



THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

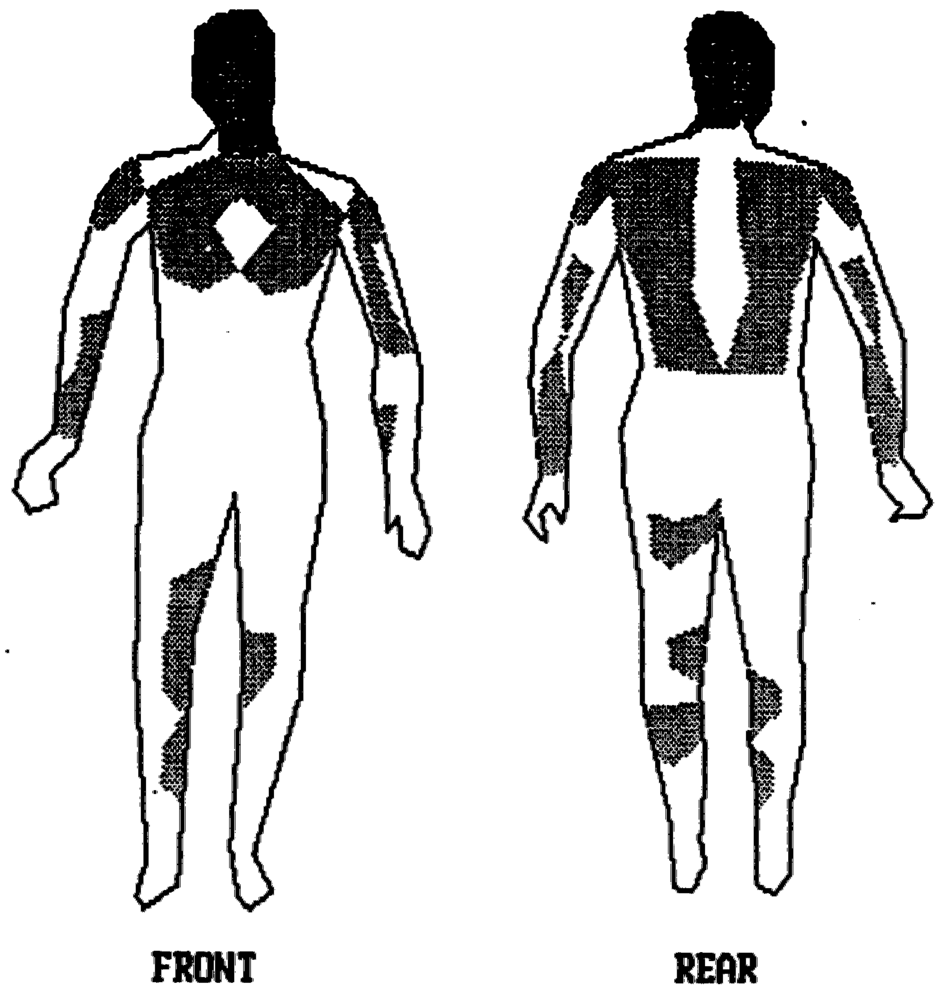
Fire Protective Clothing
Evaluation System

05-27-1993
5.2 Aramid Shirt&Pant - TSZF
203 g/sq.m

Exposure 75.0 kW/m2
Exposure Time 3.5 sec
Time of Plot 60.0 sec

2nd Deg Burn 22.50%
3rd Deg Burn 7.65%

TOTAL BURN 30.15%

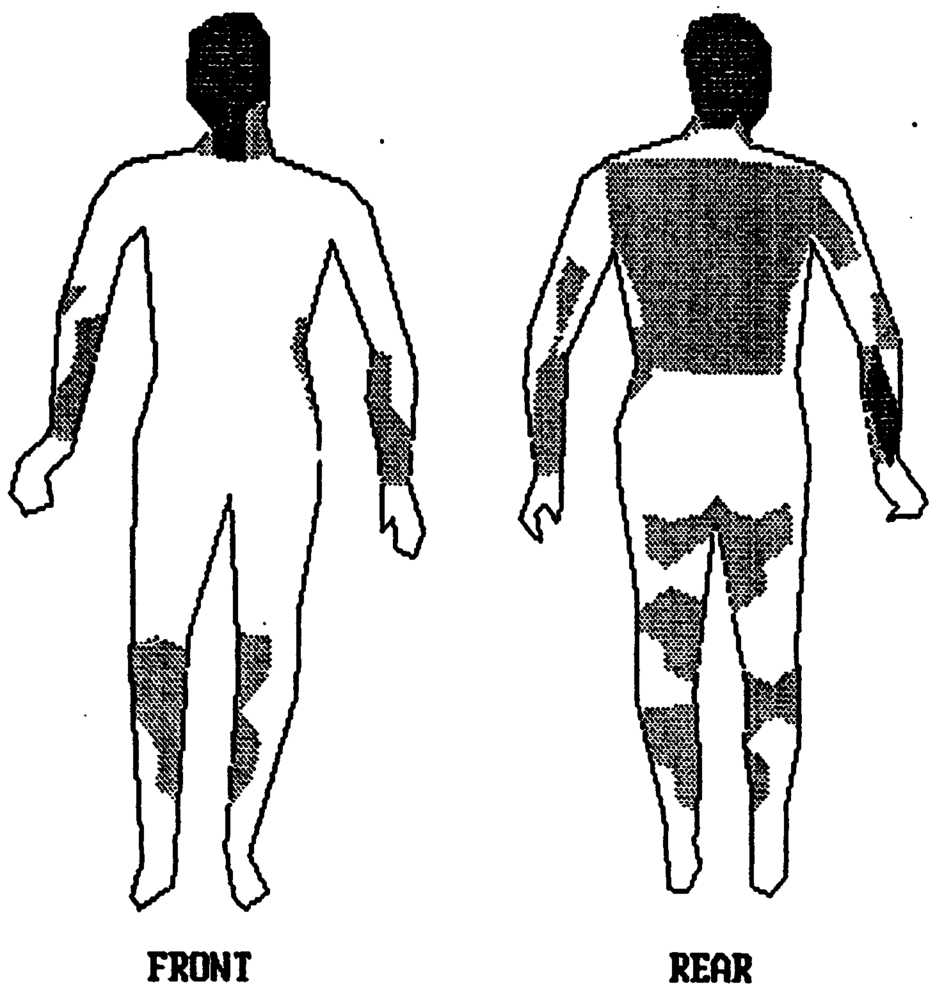


THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

Fire Protective Clothing
Evaluation System

05-26-1993
6.2 Aramid Shirt&Pant TRCS
203 g/sq.m

Exposure	75.0 kW/m2
Exposure Time	3.5 sec
Time of Plot	60.0 sec
2nd Deg Burn	20.35%
3rd Deg Burn	8.30%
TOTAL BURN	28.65%



THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

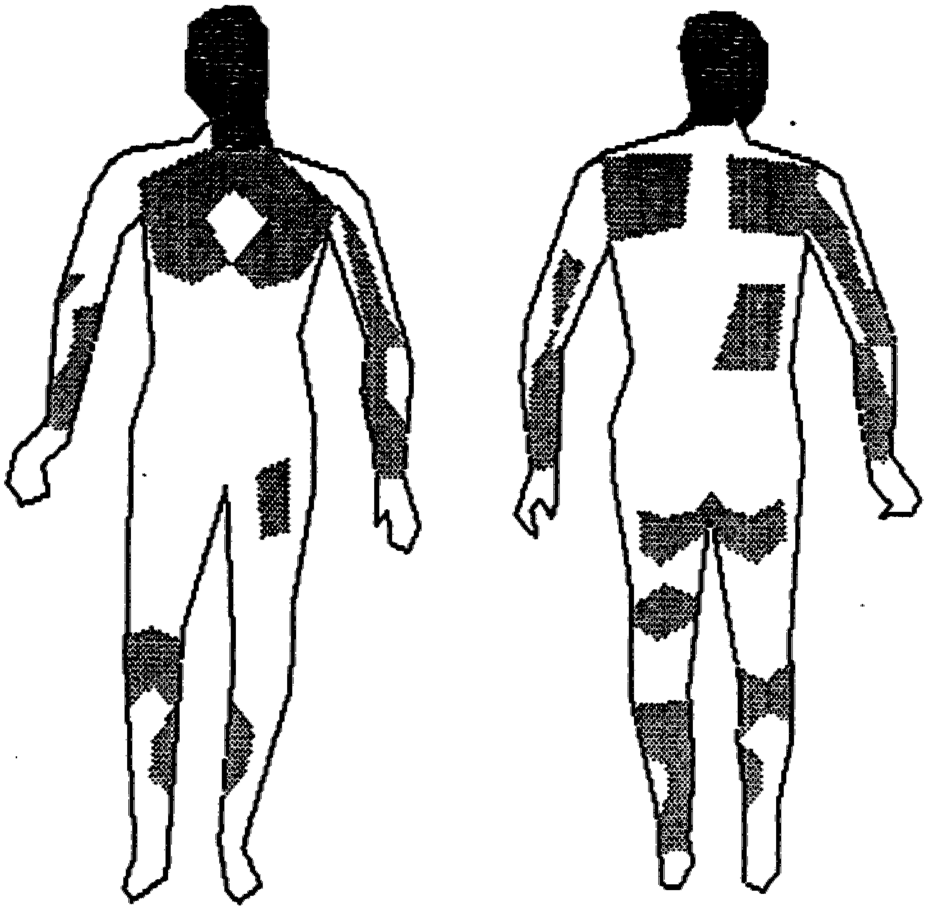
Fire Protective Clothing
Evaluation System

05-27-1993
7.1 Aramid Shirt&Pant - LSZF
203 g/sq.m

Exposure 75.0 kW/m2
Exposure Time 3.5 sec
Time of Plot 60.0 sec

2nd Deg Burn 23.85%
3rd Deg Burn 8.30%

TOTAL BURN 32.15%



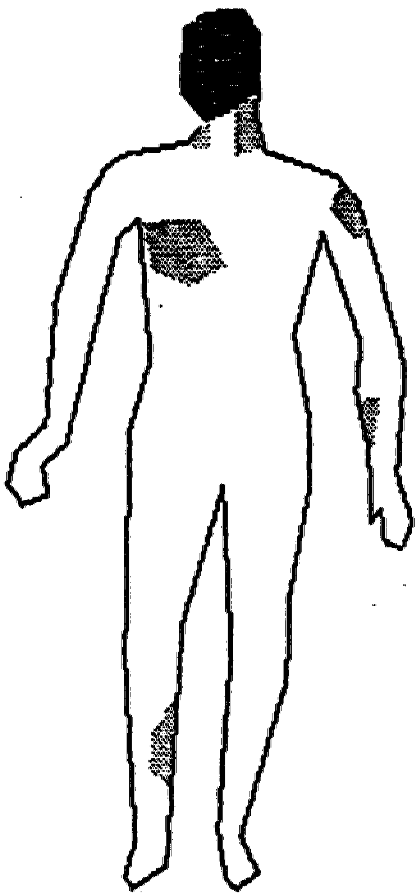
FRONT REAR

THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

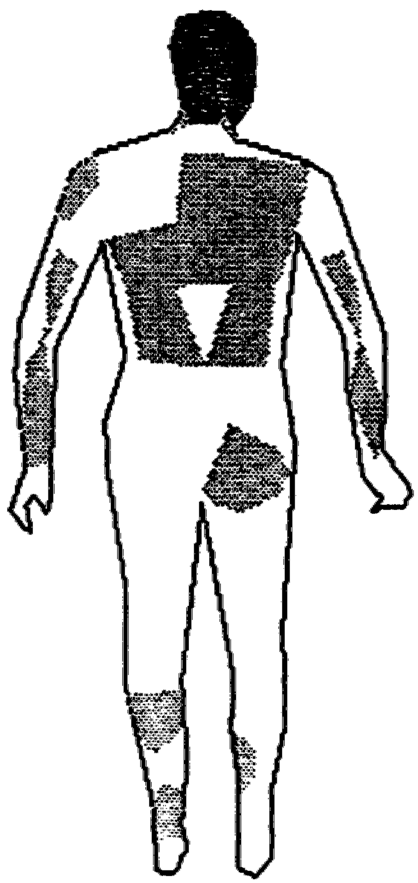
Fire Protective Clothing
Evaluation System

05-27-1993
8.3 Aramid Shirt&Pant LRCS
203 g/sq.m

Exposure	75.0 kW/m2
Exposure Time	3.5 sec
Time of Plot	60.0 sec
2nd Deg Burn	21.85%
3rd Deg Burn	8.30%
TOTAL BURN	30.15%



FRONT



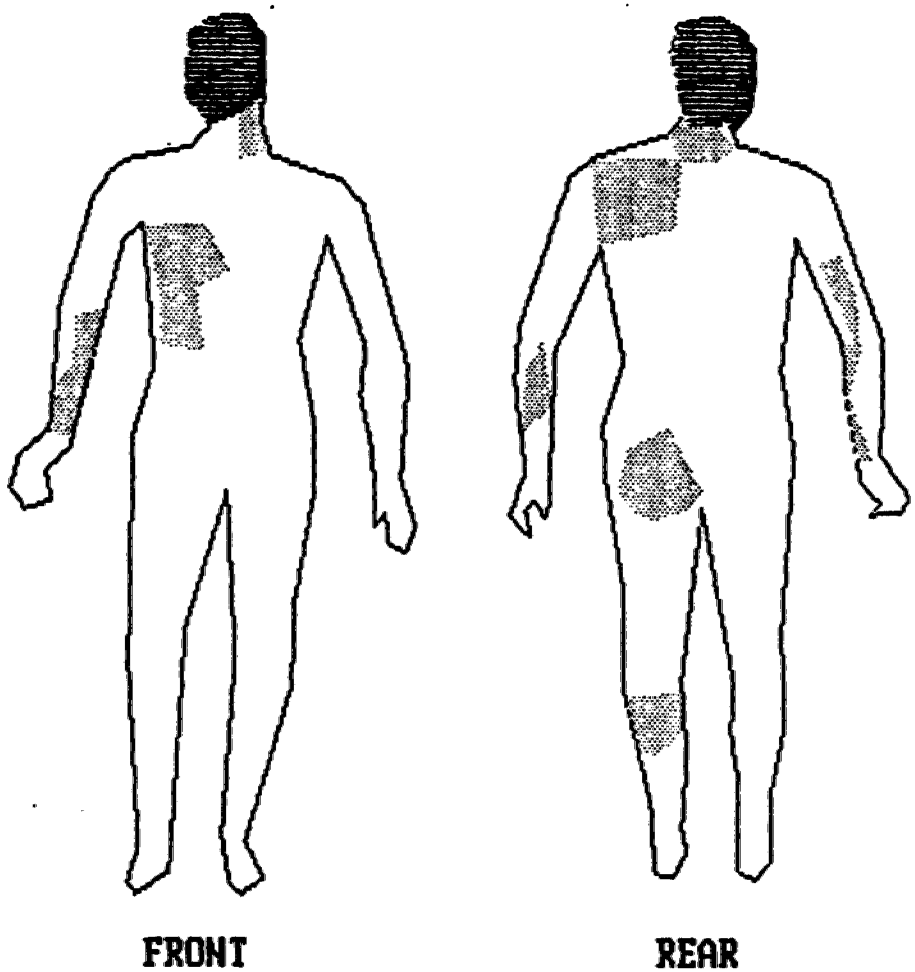
REAR

THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

Fire Protective Clothing
Evaluation System

07-16-1993
9.1 Rayon/Aramid 2 pc tight
290 g/sq.m

Exposure	80.0 kW/m2
Exposure Time	3.5 sec
Time of Plot	60.0 sec
2nd Deg Burn	15.05%
3rd Deg Burn	7.00%
TOTAL BURN	22.05%



THE UNIVERSITY OF ALBERTA
DEPARTMENT OF
CLOTHING AND TEXTILES

Fire Protective Clothing
Evaluation System

07-16-1993
10.2 Rayon/Aramid 2pc Loose
290 g/sq.m

Exposure 75.0 kW/m2
Exposure Time 3.5 sec
Time of Plot 60.0 sec

2nd Deg Burn	8.50%
3rd Deg Burn	7.00%
TOTAL BURN	15.50%

APPENDIX 7

Shrinkage of Pant Legs in the First Round of Mannquin Testing

TEST RESULTS: Shrinkage of Pant Legs - measurements taken along the inseams

Garment	Left Leg - held down by chain			Right Leg		
	Before	After	% change	Before	After	% change
Coverall T SZF						
1.1	77	66	15	77	62	20
1.2	76	70	8	76	62	18
1.3	77	70	10	76	65	15
average	77	69	11	77	63	18
Coverall T RCS						
2.1	76	74	3	76	67	12
2.2	76	75	2	76	69	10
2.3	77	72	7	77	71	8
average	77	74	4	77	69	10
Coverall L SZF						
3.1	77	74	5	77	62	20
3.2	80	71	11	80	65	19
3.3	79	72	8	79	67	15
average	79	72	8	79	65	18
Coverall L RCS						
4.1	79	72	8	79	70	11
4.2	79	74	6	79	69	13
4.3	79	74	6	79	64	19
average	79	73	7	79	67	15
Shirt & Pants T SZF						
5.1	77	70	10	77	67	13
5.2	77	70	10	77	67	13
5.3	77	74	5	77	66	15
average	77	71	8	77	67	14
Shirt & Pants T RCS						
6.1	79	74	6	77	69	11
6.2	80	71	11	77	69	11
6.3	79	74	6	79	69	13
average	79	73	8	78	69	12
Shirt & Pants L SZF						
7.1	77	69	11	77	67	13
7.2	79	70	11	79	66	16
7.3	79	71	10	79	65	18
average	78	70	11	78	66	16
Shirt & Pants L RCS						
8.1	79	75	5	77	70	10
8.2	79	74	6	79	70	11
8.3	79	74	6	79	70	11
average	79	74	6	78	70	11

Average Percent Shrinkage by Leg and Closure Style

Closure	Left Leg %	Right Leg %
Cuffs	6	12
Zippers	10	16

APPENDIX 8

Photographs of the Two Seam Types
Following Mannequin Testing

Photographs were taken out due to poor copy quality

(Page 135: photograph of flat felled seam on garment 7
after 3.5sec exposure
photograph of serged seam on garment 8 after
3.5sec exposure)

APPENDIX 9

Photographs of Selected Flightsuits
Following Mannequin Testing

Photographs were taken out due to poor copy quality

(Page 137: 1st round of testing. Garment 1 after 3.5sec exposure;
1st round of testing. Garment 2 after 3.5sec exposure.

Page 138: 1st round of testing. Garment 3 after 3.5sec exposure;
Close-up of back showing reduction of fullness through thermal shrinkage.

Page 139: 1st round of testing. Garment 4 after 3.5sec exposure;
Close-up of back showing reduction of fullness through thermal shrinkage.

Page 140: 1st round of testing. Garment 5 after 3.5sec exposure;
1st round of testing. Garment 8 after 3.5sec exposure (showing reduction of fullness through thermal shrinkage).

Page 141: 2nd round of testing. Garment 9 after 3.5sec exposure;
2nd round of testing. Garment 10 after 3.5sec exposure.)