Design and Evaluation of Thermal Protective Flightsuits Part I: The Design Process and Prototype Development

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Abstract

An aviator's flightsuit must protect against hazardous thermal environments. In addition, it must be comfortable, fit properly, allow for mobility, and meet several other expectations for military clothing. A systematic approach to designing protective garments is needed to ensure acceptance on all criteria.

The purpose of this study was to design and evaluate garment systems for optimum thermal protection for Canadian Forces flight personnel and to determine the effect of selected garment parameters (style, fit, closure system and seam type) on thermal protection. Part I focuses on the design process. Orlando's (1979) functional apparel design process served as the conceptual framework; for this study the process incorporated a literature search, material analysis, focused group interviews and movement analysis to develop design criteria and specifications for eight alternative flightsuits incorporating the parameters of interest. The design criteria included thermal protection, other functional requirements, psychological requirements, production and maintenance. Patterns for the garments were developed using AutoCAD® and PCPattern® software. The design process allowed systematic consideration of all related aspects of the problem. Evaluation of the garments is described in Part II.

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Introduction

Fire hazard has been one of the most severe dangers faced by military personnel. Studies of thermal protective garments for operational military personnel have been conducted since World War II, when the wide range of temperatures encountered by U.S. military personnel prompted extensive military research programs on clothing for protection against temperature extremes. Since then, related technologies have been developed considerably.

Flight personnel have particular concerns regarding thermal protection. Fire associated with aircraft accidents is a major cause of mortality and morbidity in military aircraft operations (Albright, Knox, Dubois, & Keiser, 1971), resulting from the unavoidable need for large quantities of highly flammable fuel on board and limited exit facilities (National Materials Advisory Board, 1977). Most aircraft fires result from crashes involving 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 post-crash fire.

Research on thermal protective clothing for military personnel has emphasized thermal protective properties of fabrics and fabric systems. The thermal protection offered by a garment depends not only on the properties of the fibres used but also on a wide range of interrelated factors including fabric structure, garment design and assembly of

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garment layers. The nature of pilots' work demands flightsuits with both thermal protection and other functional characteristics. 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. The lack of a systematic approach to designing protective garments has contributed to their poor acceptance by users (Van Schoor, 1989). Thus, a comprehensive functional design process that attempts to overcome complex design problems is appropriate in designing protective garments. A designer is able to follow a step-by-step, strategy-controlled process from the general request for the design to the garment's completion and evaluation.

The **purpose** of this study was to design and evaluate alternative garment systems for optimum thermal protection for Canadian Forces (CF) flight personnel, and to determine the effect of garment design parameters on thermal protection. This research followed a design process that incorporated an extensive literature search, material analysis, focused group interviews and movement analysis to develop design criteria and specifications for the alternative flightsuits. The **specific objectives** of this research were as follows:

1. to obtain subjective data from users (CF flight personnel) regarding both their needs and the suitability of previous and current flightsuits;
2. to employ a functional design process in the development, for Canadian Forces flight personnel, of eight different thermal protective flightsuits that vary in style, fit, closure system and seam type; and
3. to determine if there are differences in thermal protection among the eight garment designs exposed to a simulated flash fire.

Part I of this paper focuses on the first two objectives. Part II focuses on the third objective.

Related Literature

There is little information available on burn incidents involving pilots. Only one accident report involving a Boeing helicopter in August 1982 was found in the open literature. McLaren (1985) reported that all three survivors of the helicopter accident suffered varying degrees of burns while wearing layers of clothing. One was badly burned on his back and upper legs; it appears that the bottom edge of his jacket back caught fire, causing the coverall underneath it to burn. For all three men, the area of the jacket or coverall that corresponded to the burned area of skin had burned or melted and adhered to the underwear. There was no damage to the underwear layer, made of either cotton or polyester/cotton, yet sufficient heat was transferred to burn the skin.

Garment design and the arrangement of garment layers are important factors greatly affecting thermal protection. Since the 1960s, researchers have conducted extensive studies on flightsuits in order to develop desired protective properties. Researchers at the U.S. Army Natick Laboratories designed a double layered Nomex® flight coverall (Oakes & Maj, 1967). Although this garment was quite protective, evaluators found it warmer and less comfortable than the standard Army flightsuit. In 1970, the U.S. Air Force Materials Laboratory examined the extent of body burn damage when mannequins were clothed in flightsuits of several candidate fabrics. It was found that garments of PBI® fabric offered the best thermal protection (Schulman & Stanton, 1971).

In the late 1970s, a program undertaken at the U.S.A.'s Naval Air Development Center (NADC) led to the development of a double-knit, high-temperature resistant, aramid fabric for flight coveralls. The favourable characteristics of knit construction included lower cost, improved comfort, more freedom of movement, and better fit and aesthetic appeal. The fabric stretched, however, when worn for extended periods, and was prone to snagging (Lewyckyj and Reeps, 1978). An aramid coverall was developed by the Navy Clothing and Textile Research Facility in the mid 1980s (Boutin, 1984). With the exception of a pencil pocket and shoulder epaulets, the coverall design was the same as that of the Air Force CWU-27/P coverall. Twelve of these garments were tested on a mannequin for protection against fire at the NADC fuel fire test facility. All but one was flaming as they emerged from the fire pit, and all quickly self-extinguished. The mean percentage of body burned was 26.8.

The Design Process

Designing a protective garment incorporating relevant factors is a complex task that involves objectifying the design process so that the resulting design meets specific needs (Orlando, 1979). Jones (1970, 1981) proposed a self-organizing design system that combines the search for the design (creative process) with an evaluation of the search pattern (strategy control). Orlando followed Jones' approach in developing a **functional apparel design process** used primarily in the design of special purpose apparel. Orlando's process is a comprehensive, externalized, strategy-controlled approach that attempts to overcome complex design problems. Although not necessarily linear, the process generally comprises several stages: a general request for the design, exploration of the design situation and problem structure, development of design criteria and specifications as well as an interaction matrix, prototype development and evaluation. A similar process has been described by Rosenblad-Wallin (1985).

Details of the process and strategies developed specifically for this research are described here. The **general request** was to design flightsuits to provide optimum thermal protection for CF flight personnel. To **explore the design situation** thoroughly in the early stages of the process, observation of both video tapes and photographs of previous mannequin testing of thermal protective clothing was necessary. Viewing a television program about American pilots and planes was also helpful to the designer. Several aspects of the first phases of the process

(market analysis, material and garment analyses) were completed in earlier related projects (Crown and Dale, 1992; Crown, Ackerman, Dale and Rigakis, 1993). For this project, both focused group interviews and videotaped movement analyses were conducted to better understand the problem structure.

Focused Group Interviews

Focused group interviews were conducted at Canadian Forces Base Edmonton. The interview protocol, including recruitment notice, information for participants and consent form, met University of Alberta's requirements for ethical human research. Non-random purposive samples of eight and ten male aircrew members volunteered for two interview groups: helicopter pilots and transport pilots. The interviewer asked each participant to write down his likes and dislikes regarding current and past flightsuits and then to report them verbally. After an open discussion of the responses, participants were asked more specific questions about flightsuit design.

All participants provided extensive data in the interview. The likes and dislikes regarding current flightsuits are summarized in Table 1. The pilots agreed that fit, comfort and safety are the three most critical criteria for flightsuit design. To improve fit, a more complete range of sizes than is currently available is needed for one- and two-piece flightsuits. With respect to comfort, some participants reported that current flightsuits' high percentage of wool (65/35 wool/polyester blend) makes them hot and scratchy. Additionally, the garments become rougher when pilots perspire. These discomforts reportedly reduce a pilot's working efficiency. Participants believed that cotton would provide comfort but not the thermal protection so critical for flightsuits.

One participant in each interview group had experienced a fire accident and reported that this experience changed his attitude regarding the importance of a garment's thermal protection. These pilots had previously considered thermal protection less important than comfort, but one reported that after the accident he bought thermal protective underwear for himself, indicating the importance he now placed on such protection.

Participants believed that the flightsuits' current wool/polyester blend does not provide much thermal protection. Some pilots thought that Nomex® (aramid) would provide the safety that flightsuits require. Some participants preferred Nomex® over their current wool/polyester flightsuits, believing that it would be more comfortable.

Garments with adjustable Velcro® (hook and pile) tape at waist and cuffs were suggested by participants for better fit. Also, pilots consider numerous pockets necessary because they cannot carry briefcases when they fly or work in the field, and all accessories and tools are carried in their pockets.

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

Likes	Dislikes
Two-piece Green Flightsuit	
1. Easy to go to toilet while in the field	1. Bad fit (limited size range)
2. Many pockets are well-placed	2. Big waist
3. Clips for map	3. Hot and itchy
4. Scribble pads on thigh	4. Crotch too deep; bad cut
5. Color suitable for the military	5. Shirts too long
6. Closed flap on pencil pocket	6. Sleeve cuffs too tight
	7. Convertible collar too floppy; interferes with shoulder harness
	8. Sleeves too tight & too short; cannot roll up sleeves
	9. Back pockets add thickness and are useless
	10. Zippers on lower leg pockets too high when kneeling
	11. Needs dry cleaning; not easy care
	12. Pants are hard to hold up
	13. Wallet and knife pockets too long and too low
	14. Plastic clips not flame resistant
	15. Poor workmanship
One-Piece Blue Flightsuit	
1. More comfortable fabric[a]	1. Color not suitable for military uniform
2. Less hot (than green one)[a]	2. No scribble pad
3. Fits well	3. No pocket on right leg
4. Pockets and zippers well placed	4. Hot and itchy
5. Adjustable waist	5. Convertible collar too floppy and interferes with shoulder harness
6. More similarity to other countries' uniforms	6. No flap on low pencil pocket
7. Clips on both legs	7. Lower leg pockets too long
8. Greater variety of size available	8. Sleeves too tight & too short; cannot roll up sleeves
	9. No thermal protection after washing
	10. Poor workmanship

[a]In fact, both suits were made from the same fabric; only the color varied.

Movement Analysis

Video taping recorded movement for analysis. Two pilots from each interview group were asked to simulate their typical daily activities in and around their planes while wearing their current one-piece and two-piece flightsuits. When pilots in the cockpit are operating aircraft, they need to stretch their arms in front of them and over their heads to reach the operational instruments. The arm movement can be described as flexion (Watkins, 1984, p. 148) around the shoulder, in which the arms make a half circle from the vertical rest position through front horizontal to vertical above the head. Therefore, the garments require enough ease for each arm movement. One can see in the video recording that the pilots' flightsuits are strained both across the back and at the underarm, especially when their arms are raised, preventing the pilots from moving their arms comfortably. Helicopter pilots perform 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. The flightsuit design thus should accommodate movement in such activities.

Design Specifications and Interaction Matrix

Based on the results of the previous phases of the process, design specifications were developed in detail for each of five principle criteria: safety or thermal protection, other functional requirements (comfort, fit/mobility), psychological requirements, production and maintenance. An interaction matrix of design specifications was then established (Table 2). At this point, both comfort and maintenance-related specifications related to materials rather than to garment design were omitted. The interaction matrix was used to illustrate specifications that were in direct conflict with each other (0), specifications that required accommodation to be met in the same garment (1), and specifications that created no conflict (2).

Two pairs of specifications in the matrix were defined as being in direct conflict. Specification #2, "cover limbs completely," directly conflicted with #7, "sleeve can be rolled up to cool off." Current flightsuits displayed this

Table 2. Interaction Matrix of Garment Specifications for Flightsuit Design

Principle Criteria	Specification:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Thermal Protection	1 cover torso completely		2	2	1	2	1	2	2	2	2	1	1	1	2	2	2	2	1	1	2[a]
	2 cover limbs completely (with gloves and 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
Functional Requirements	4 garment system should be appropriate for both cold and hot weather					1	**2**	2	2	2	2	**2**	1	1	2	2	2	2	1	1	2
	5 collar should prevent chafing by seat belt, etc.						1	2	2	2	2	2	1	1	2	2	2	2	1	1	2
	6 garment design should allow evaporation of perspiration							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 should fit at crotch											2	1	1	2	2	2	2	2	2	2
	11 should be adjustable to provide better fit												2	1	2	2	2	2	1	1	2
	12 should allow smooth movement and full extension of the arms, etc.													1	1	1	2	2	1	1	2
	13 should provide adjustable closures for easy on/off operation														1	1	1	2	1	1	2
	14 should provide sufficient pockets for equipments and other needed accessories															1	1	2	1	**0**	1
	15 garment shape and fit should not be distorted by insertion of equipment into 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 cause discomfort																		2	2	1
Psychological Requirements	18 style should have familiarity among military personnel																			1	2
	19 should be neat in appearance																				2
Production	20 should be capable of mass production with good quality																				

[a]O = Conflict; 1 = Accommodation; 2 = No conflict

conflict explicitly in that the sleeve cuffs had limited adjustment, and the pilots could not roll up their sleeves even in hot weather because of the narrow sleeve opening. The current design apparently sacrificed comfort for the purpose of protection. Another pair of design specifications possibly in direct conflict is #14, "garment should provide sufficient pockets for equipment and other needed accessories," and #19, "garment should be neat in appearance." Participants in the interview considered having numerous pockets on a garment more important than neat appearance; thus, it was decided that the design meet the most important criterion and compromise a neat appearance.

Although some pairs of specifications did not directly conflict, they required design accommodation so that both could be met. One such example is in the relationship between #12 ("garment should allow smooth movement and full extension of the arms,") and #14 ("garment should provide sufficient pockets for equipment and other needed accessories"). A garment with many accessories in the pockets might interfere with the wearer's movement. The shapes and location of the pockets therefore needed to facilitate smooth movement.

Prototype Development

The flightsuit designs incorporated the design specifications from Table 2 and varied on four parameters. Defence Research Establishment Ottawa (DREO) requested comparison of these parameters of style, fit, closure system, and seam type (Table 3). Because it was expected that seam type would have little effect on a garment's thermal protection, seam type was varied with closure system; thus, eight different flightsuits incorporating the four parameters of interest were designed on the computer using AutoCAD® and PCPattern® software. The size 42 pattern pieces of the current one-piece flightsuit, including all pocket pieces, were digitized into a computer and the new experimental designs were developed incorporating the design specifications from Table 2.

One-Piece Flightsuits (Figure 1)

The current one-piece coverall was considered a close-fitting garment. Patterns for experimental designs 1 and 2 were therefore developed as modifications to the current garment. Modifications were made on the sleeves to allow freer movement. In particular, armholes on both front and back bodice pattern pieces were lowered 10 mm to give more room and allow full arm extension. For garment 1, the closure system including collar, front closure, and sleeve and leg closure conformed to closure system A (Table 3). For garment 2, closure system B was incorporated while the major pattern pieces are unchanged from those of garment 1.

Loose-fitting coveralls (garments 3 & 4) were developed from the close-fitting garment patterns. Garment 3 was based on the pattern for garment 1 with closure system A, and garment 4 was based on garment 2 with closure system B. Movement analysis revealed that the bodice back is strained when pilots extend their arms forward; therefore, this area requires extra fullness. Two 70 mm flanges were added to both the front and back bodices of the coverall to produce a much looser garment. Additional 30 mm tucks were added to the front shoulder. Chest pockets were modified to accommodate the front flanges. The original darts on the front and back bodice and back pant were changed to tucks to give the garment extra fullness. Additional 50 mm tucks were added to the front pant and 40 mm tucks to the back pant at the waist. The two-piece sleeves were replaced by looser-fitting one-piece sleeves. One 70 mm inverted pleat was added along the center of each sleeve.

Table 3. General Description of Eight Flightsuits, Incorporating Four Parameters

Garment	Style	Fit	Collar and Closure System	Seam Type
1	one-piece	close	A (stand-up collar, exposed front zipper, zipper on sleeves and pant legs)	flat felled
2	one-piece	close	B (convertible collar, hidden front zipper, cuff with Velcro®)	serged
3	one-piece	loose	A	flat felled
4	one-piece	loose	B	serged
5	two-piece	close	A	flat felled
6	two-piece	close	B	serged
7	two-piece	loose	A	flat felled
8	two-piece	loose	B	serged

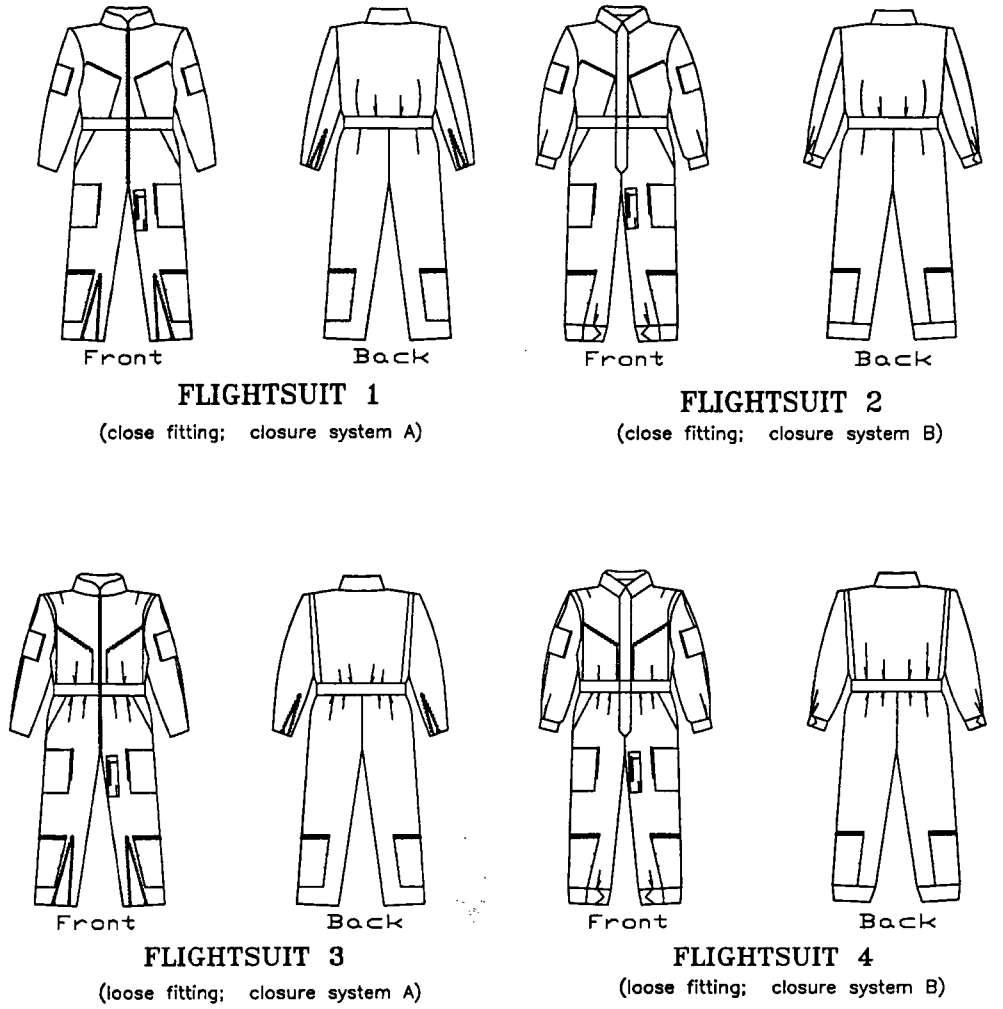

Figure 1. Details of One-Piece Flightsuit

Two-Piece Flightsuits (Figure 2)

Because many participants complained about the fit of the current two-piece flightsuit (Table 1), patterns for the shirts and pants of the close-fitting suits (garments 5 & 6) were created by adapting the size 42 sloper pattern for men's shirt and pants available as part of the PC Pattern® program. Modifications were made to the sloper patterns according to the design specifications. This style fitted much closer than the current two-piece garment. For example, the pattern for the experimental shirt back is 50 mm narrower at the underarm, and the shirt length is 50 mm shorter than the current design. The armhole was also lowered to provide more arm movement, and the sleeves were lengthened 20 mm to cover the arms completely when stretched. Pilots' additional complaint that the current pant crotch is too deep prompted making the new crotch depth 50 mm shorter. Velcro® adjustments were added to each side of the pant waist.

Loose-fitting two-piece suits (7 & 8) were developed from the patterns for the close-fitting shirts and pants. Two 60 mm pleats were added to the shirt back below the yoke. Rather than adding flanges to the shirt front, the front chest was enlarged by 15 mm at each side of the underarm and a 30 mm tuck was added at the front shoulder to give more ease. The sleeve sloper in PCPattern® was modified by adding a 70 mm inverted pleat along the center of each sleeve. To incorporate controlled fullness into the pants, they were designed with elasticized waists with Velcro® adjustments at each side.

Closure Systems, Seams, and Other Design Elements

The closure system on thermal protective garments requires special attention. Closure systems for flightsuits include collar, front openings, and sleeve and leg openings. Both current flightsuits have convertible collars, exposed front zippers, cuffed sleeve closures, and zippered leg closures. Two alternative closure systems were chosen for the new designs. Specifically, closure system A (garments 1, 3, 5, & 7) includes a stand-up collar, an exposed front zipper with a zipper guard underneath, and godet-type zipper closures on sleeves and pant legs; closure system B (garments 2, 4, 6, & 8) includes a modified convertible

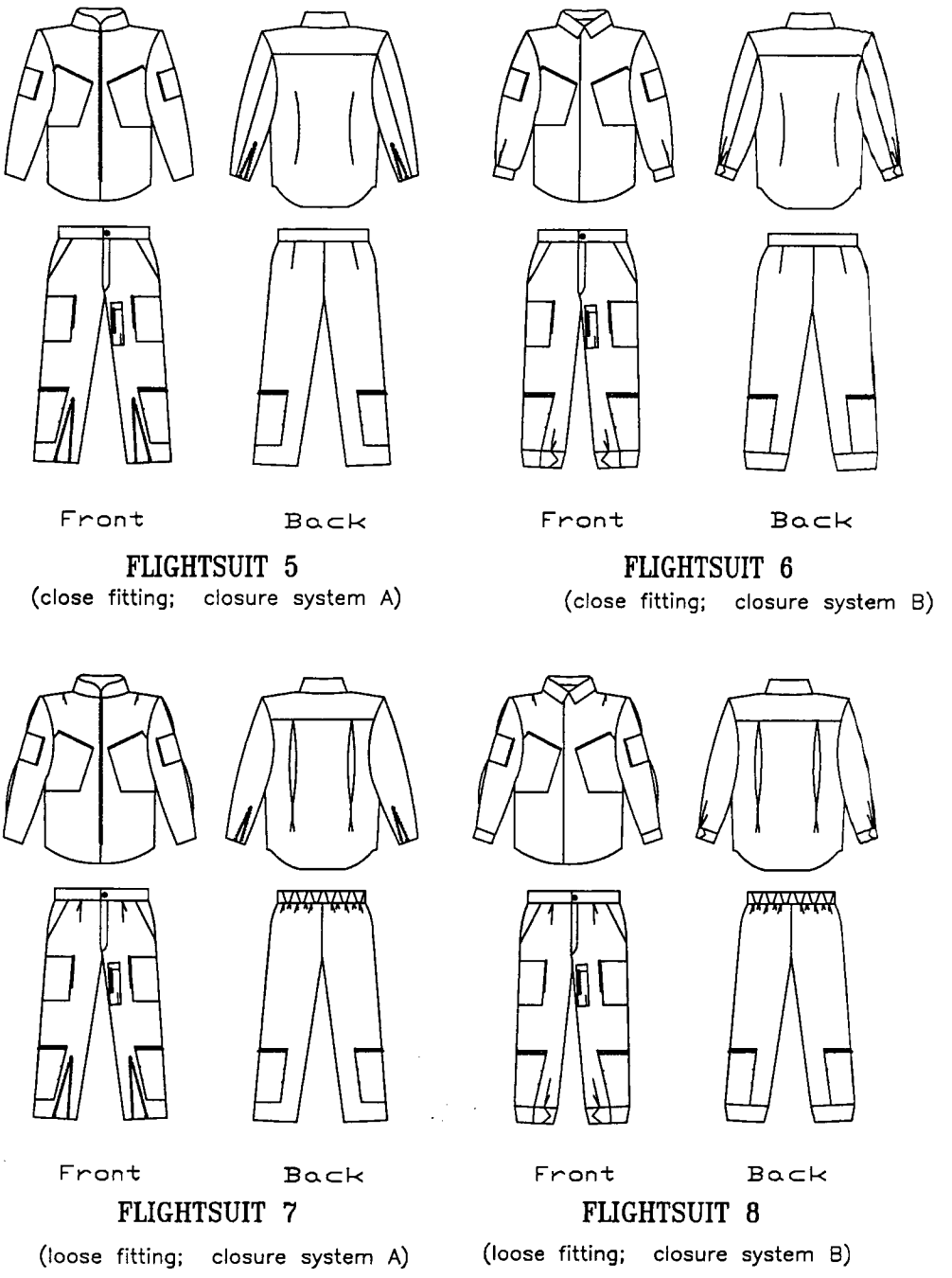

Figure 2. Details of Two-piece Flightsuit

collar, a hidden front zipper, and cuffs with Velcro® closure on the sleeves and pant legs.

Collar: Pilots complained that convertible collars on current garments are "floppy" and lie flat on the shoulder, leaving the neck exposed in a fire accident. In addition, they reported that the current collar interferes with shoulder harnesses worn during flight. A stand-up collar was therefore chosen as one alternative to better protect the neck area and prevent harness chaffing. This collar was used in closure system A. The second collar, used in system B, was a modification of the current convertible collar incorporating an S-curve on the neckline, enabling the collar to stand more vertically and fit more closely around the neck for improved protection.

Front Closure: The current flightsuit front closure, an exposed zipper with zipper guard underneath, was used in closure system A. The second alternative, a hidden zipper front opening, was used in closure system B.

Sleeves & Legs Closures: Two closure options were chosen for sleeves and legs: zipper closures and cuffs with

Velcro®. As participants indicated, current flightsuits' cuffed sleeve closure with a small opening allows only limited adjustment and does not allow the sleeves to be rolled up. A godet-type zipper closure was used on the sleeves in the new designs as one alternative to remedy this problem, allowing pilots to open the zipper and push up the sleeves to cool off. The zippered leg closure on the current flightsuits was not changed for closure system A.

In closure system B, the current cuffed sleeve closure was not altered and was used for the closure on the pant legs. To allow more freedom of arm movement, the cuffed sleeves were made 20 mm longer than the originals. (The length of the sleeves with zippered closures in system A was not changed, because if the sleeves are too long, the zippered closure cannot hold the sleeves in place above the wrist as the cuffed closure does.)

Seam types: Flat-felled seams were chosen for use in garments 1, 3, 5, and 7, to be compared with four-thread serged seams in garments 2, 4, 6, and 8.

Other Important Features: Several modifications were made to the design and placement of pockets to accommodate the pilots' stated requirements (Tan, 1994), but are not described in detail here because they have little relevance to protective performance.

Prototype Production

The eight flightsuits were fabricated into muslin prototypes and fitted on the instrumented mannequin used to evaluate and compare the garments. Minor corrections were made to the prototype muslin garments to improve fit and to facilitate donning and doffing operations. After changes and corrections were incorporated in the computer-generated patterns, markers were made of each design and were sent to a local manufacturer for production of the test garments.

Discussion Regarding the Design Process

Orlando's (1979) **Functional Design Process** served as the framework for this research. The general request for the design helped the designer identify the nature and purpose of the study. Full exploration of the design situation, a frequently overlooked part of the design process, allowed the designer to obtain much data relevant to thermal protective clothing, providing general but necessary information for the design of the flightsuits. Strategies such as focused group interviews, detailed literature search, a market analysis, and material and garment analyses, permitted close examination of the problem structure. The results of the initial stages of the process informed the establishment of five principle design criteria. This stage helped the designer consider all related aspects completely and incorporate all the relevant factors into the design specifications. An interaction matrix was useful in determining priorities among specifications. For example, when thermal protection conflicted with comfort, two alternative sleeve closures were designed, each meeting a different requirement better than the other. Based on the established specifications and their inter-relationships, patterns for the flightsuits were designed and garments produced. Specifications also serve as criteria for evaluation.

In sum, the **functional design process** allowed the designer to follow a step-by-step, strategy-controlled procedure from the general request for the flightsuit design to prototype garment completion and evaluation. Such process enabled the designer to incorporate required design elements and specifications into the final designs to meet the pilots' needs.

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