B.S. 12

USAARL REPORT NO. 78-9

EVALUATION OF FOUR THERMALLY PROTECTIVE FABRICS USING THE USAARL BIOASSAY METHOD

By

Francis S. Knox, III
Thomas L. Wachtel
George R. McCahan, Jr.

June 1978

U.S. ARMY AEROMEDICAL RESEARCH LABORATORY
FORT RUCKER, ALABAMA 36362

USAARL

NOTICE

Qualified requesters may obtain copies from the Defense Documentation Center (DDC), Cameron Station, Alexandria, Virginia. Orders will be expedited if placed through the librarian or other person designated to request documents from DDC.

Change of Address

Organizations receiving reports from the U. S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

Distribution Statement

This document has been approved for public release and sale; its distribution is unlimited.

Disclaimer

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

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

14

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
USAARL [redacted] 78-9

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6 EVALUATION OF FOUR THERMALLY PROTECTIVE FABRICS USING THE USAARL BIOASSAY METHOD

5. TYPE OF REPORT & PERIOD COVERED
9 Final Report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
10 F. S. Knox, III, T. L. Wachtel [redacted] G. R. McCahan, Jr

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
US Army Aeromedical Research Laboratory
P. O. Box 577
Fort Rucker, AL 36362

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
6.27.73.A 3E62173A819 015

11. CONTROLLING OFFICE NAME AND ADDRESS
US Army Medical Research & Development Command
Fort Detrick
Frederick, MD 21701

12. REPORT DATE
11 June 1978

13. NUMBER OF PAGES
35

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
16 3E762773A819

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

12 36p.

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release and sale; its distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES a. Presented at Tenth Scientific Session of the Joint Committee on Aviation Pathology, September 1976, Royal Air Force Institute of Pathology and Tropical Medicine, Halton, England. b. Submitted for publication in Aviation, Space and Environmental Medicine under title Bioassay of thermal protection afforded by candidate flight suit fabrics.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Thermally Protective Fabrics	Bioassay
Burn Protection	Flight Suits
Safety	Swine
Skin	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The United States Army Aeromedical Research Laboratory (USAARL) porcine cutaneous bioassay technique was used to determine what mitigating effect four thermally protective flight suit fabrics would have on fire-induced skin damage. The fabrics were 4.8 oz twill weave Nomex® aramide, 4.5 oz stabilized twill weave polybenzimidazole, a 4.8 oz plain weave experimental high temperature polymer, and 4.8 oz plain weave Nomex® aramide. Each fabric sample was assayed 20 times

over

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

404578

20. ABSTRACT (Cont'd)

SQ Cm

in each of four configurations: as a single layer in contact with the skin; as a single layer with a 6.35 mm (one-fourth inch) air gap between fabric and skin; in conjunction with a cotton T-shirt with no air gaps; and, finally, in conjunction with a T-shirt with a 6.35 mm air gap between T-shirt and fabric. Bare skin was used as a control.

A JP-4 fueled furnace was used as a thermal source and was adjusted to deliver a mean heat flux of 3.07 cal/cm^2/sec. The duration of exposure was five seconds. Four hundred burn sites were graded using clinical observation and microscopic techniques.

Used as single layers, none of the fabrics demonstrated superiority in providing clinically significant protection. When used with a cotton T-shirt protection was improved. Protection improved progressively for all fabrics and configurations when an air gap was introduced. The experimental high temperature polymer consistently demonstrated lower heat flux transmission in all configurations but did not significantly reduce clinical burns.

FOREWORD

The vivarium of the United States Army Aeromedical Research Laboratory (USAARL) is fully accredited by the American Association for the Accreditation of Laboratory Animal Care.

The animals used in this study were procured, maintained, and used in accordance with the Animal Welfare Act of 1970 and AR 70-18. In conducting the research described in this report, the investigators adhered to the "Guide for Laboratory Animal Facilities and Care," as promulgated by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences, National Research Council.

All authors were research investigators at the USAARL during the conduct of the experiments described herein.

Dr. Knox is currently with the Department of Physiology and Biophysics, Louisiana State University Medical Center School of Medicine, Shreveport, Louisiana 71130.

Dr. Wachtel is currently with the Department of Surgery, University of California, San Diego, School of Medicine, San Diego, California 92103.

Dr. McCahan is currently with the Department of Toxicology and Criminal Investigation, State of Alabama, Enterprise, Alabama 36330.

SUMMARY

The United States Army Aeromedical Research Laboratory (USAARL) porcine cutaneous bioassay technique was used to determine what mitigating effect four thermally protective flight suit fabrics would have on fire-induced skin damage. The fabrics were 4.8 oz twill weave Nomex® aramide, 4.5 oz stabilized twill weave polybenzimidazole, a 4.8 oz plain weave experimental high temperature polymer, and 4.8 oz plain weave Nomex® aramide. Each fabric sample was assayed 20 times in each of four configurations: as a single layer in contact with the skin; as a single layer with a 6.35 mm (one-fourth inch) air gap between fabric and skin; in conjunction with a cotton T-shirt with no air gaps; and, finally, in conjunction with a T-shirt with a 6.35 mm air gap between T-shirt and fabric. Bare skin was used as a control.

A JP-4 fueled furnace was used as a thermal source and was adjusted to deliver a mean heat flux of $3.07\ \text{cal/cm}^2\text{/sec}$. The duration of exposure was five seconds. Four hundred burn sites were graded using clinical observation and microscopic techniques.

Used as single layers, none of the fabrics demonstrated superiority in providing clinically significant protection. When used with a cotton T-shirt protection was improved. Protection improved progressively for all fabrics and configurations when an air gap was introduced. The experimental high temperature polymer consistently demonstrated lower heat flux transmission in all configurations but did not significantly reduce clinical burns.

APPROVED:
STANLEY C. KNAPP
Colonel, MC
Commanding

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

Table | Page

Figure

INTRODUCTION

A free field or helicopter postcrash JP-4 fuel fire reaches maximum intensity and "steady state" thermal dynamics 20 seconds after single point ignition.[1] [2] An aviator wearing a standard summer weight cotton flight uniform who is in the middle of such a conflagration must get out of the fireball within 10 seconds after ignition if he is to have a reasonable chance of survival.[3-5] After 20 seconds, the aviator would be in a thermal environment with temperatures ranging from 927° C to 1260° C.[1] [3] [4] [6] Heat flux in controlled postcrash fires ranges from 2.79 to 7.45 $cal/cm^2/sec$*.[1] [2]

Extensive studies conducted by the U. S. Army Aeromedical Research Laboratory (USAARL) and others[1] [2] [4] [7] have shown that postcrash fires are extremely variable in their time-course and in severity. These studies led to a definition of the worst credible thermal environment as 1149° C or 5.5 $cal/cm^2/sec$.[1]

During a postcrash fire, the aviator's clothing is the only barrier between the excessive thermal environment and the skin. The design of operational flight clothing requires consideration of fabric flammability, heat transfer characteristics, comfort, launderability, abrasion resistance, fabric strength and durability, color fastness and predicted useful service life, to mention only a few important factors. Since all design parameters cannot be optimized using present technology, each garment is always a compromise product. An aviator's flight suit may never be subjected to the hazardous thermal environment against which it was designed, but this design parameter must remain among the foremost in a selection process among several candidate fabrics or designs. Obviously any selection process is complex and requires consideration of cost, logistics, and user acceptance as important considerations.

From a thermal protective standpoint any selection of fabric or garment design must be based on an appropriate set of test procedures. These methods must recreate the postcrash thermal environment in the laboratory and must quantitatively predict burns from measured thermal transfer through the fabric. For testing fabric samples, the ideal method would be to use physical thermal sensors such as calorimeters or skin simulants to measure the thermal transfer so one could predict from such data the burns that would

---

*These heat flux calculations assume black body conditions calculated from Stefan-Boltzmann Law.

result. To do this with any degree of accuracy requires a mathematical model. However, mathematical models which generate burn predictions from measured thermal transfer are not, at this time, sufficiently accurate. Therefore, the use of a bioassay technique in which porcine skin is used as a model for human skin is recommended.[4] [8] The direct bioassay technique provides burn data that are readily understandable and acceptable to physiologists and clinicians. The data require no extrapolation for the fabric engineer.

The experiments described in this report show what mitigating effects four selected thermal protective fabrics have on skin damage thermally induced by exposure to a simulated postcrash fire.

METHODS AND MATERIALS

Twenty white, cross-bred, male and female domestic swine (*Sus scrofa domesticus*) were procured locally, quarantined for at least 30 days, treated for any internal or external parasites, and verified to be healthy prior to use in this experiment. The animals were housed in a covered outdoor vivarium and weighed 43.9 ± 6.6 kg at the time of the experiment. The pigs were assigned randomly to one of four exposure groups of five animals each.

The swine were fasted overnight, premedicated with atropine (0.04 mg/kg) and fentanyl-droperidol (0.1 ml/kg), intubated and anesthetized with Halothane USP.[9] Hair was removed from the test site by close clipping with a #40 clipper head.[10] The anesthetized pigs were placed on a rolling animal carriage with an electrically activated pneumatically operated water-cooled shutter system (Figure 1, page 4). Each of the five pigs in a group received four separate exposures, two on each side, of five seconds duration to a standardized thermal source.

The thermal source was a JP-4 fueled furnace[4] which delivered 3.07 ± 0.16 $cal/cm^2/sec$ (70-90% of this energy was radiative) (Figure 1, page 4). Furnace wall temperature and heat flux were continually recorded on FM magnetic tape for later off-line computer processing. Heat flux and exposure time were found to be uniform from one position to another. Each exposure area was divided into six circular burn sites by a multi-layer asbestos/wood template (Figure 2, page 4). The holes were either 4.0 cm or 5.9 cm in diameter. Template position five always contained a slug calorimeter to monitor the fire (Figure 3A, page 5). Sites one through four and six were either covered with fabric or left uncovered as a control (Figure 3B, page 5). Four fabrics were evaluated. They were 4.8 oz twill weave Nomex® aramide, 4.5 oz stabilized twill weave polybenzimidazole, a 4.8 oz plain weave experimental high temperature polymer, and 4.8 oz plain weave Nomex® aramide (Figure 4, page 5). In the double layer configurations, the second layer always 100% cotton T-shirt (T). The textile characteristics for these fabrics are summarized in Table 1 (page 6).

From Table 2 (page 7) it is possible to determine which fabric covered a particular burn site for each pig. For example, in treatment Group III, the left rear area on pig number three had new weave Nomex® (NWN) in contact with the skin at burn site one and polybenzimidazole (PBI) in contact with 100% cotton T-shirt in contact with the skin at position four. This system of fabric layout insured that each fabric appeared in each test position four times and was tested a total of 20 times using each of the four methods of application. Thus, a five position by five fabric Latin square was replicated four times for each group.

Damage was documented photographically immediately after the exposure and 24 hours later. A clinical grade[11] was assigned immediately after exposure and again 24 hours later (Table 3, page 8).

A biopsy was taken from each site 24 hours after the exposure. This specimen included the area representing the highest clinical grade as well as contiguous normal tissue for comparison. Hematoxylin and eosin stained sections were graded according to criteria developed by Lyon, et al,[12] and Knox and Wachtel[4] (Table 4, page 9). In addition to this grade, actual burn depth was measured optically, together with measurements of the normal epidermal and dermal thicknesses. These data were analyzed using analysis of variance and covariance. Fabric effects were tested for significance by the modified Newman-Keuls' tests.

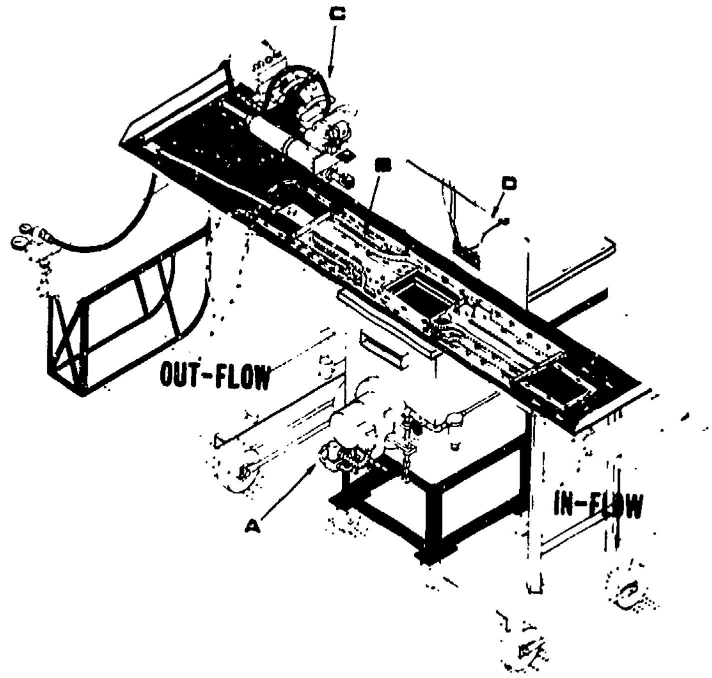

FIGURE 1. Schematic Diagram of the USAARL T-1 Furnace and Rolling Animal Carriage With the Electrically Activated Pneumatically Operated Water-Cooled System.

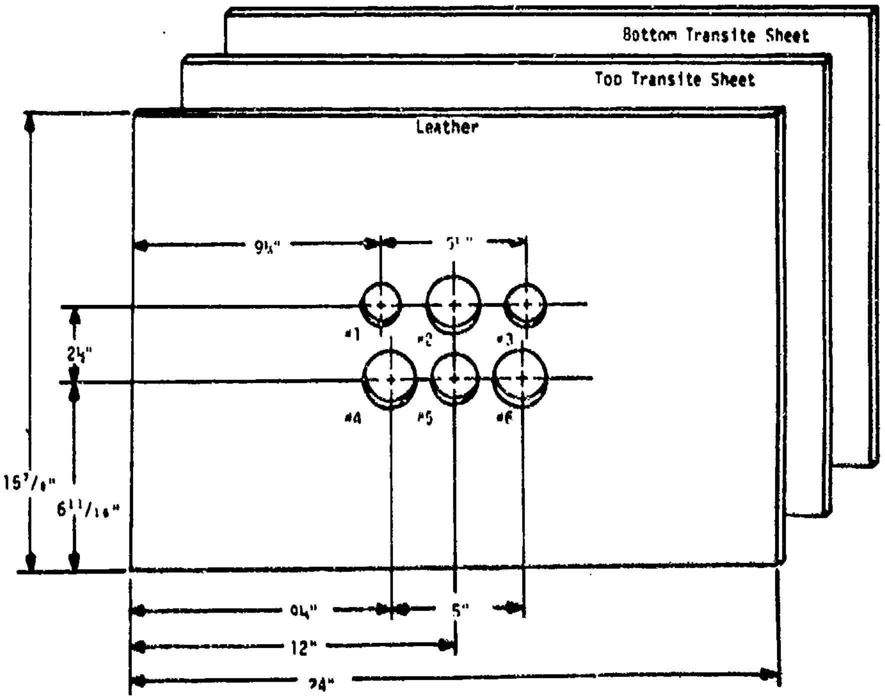

FIGURE 2. Template Design.

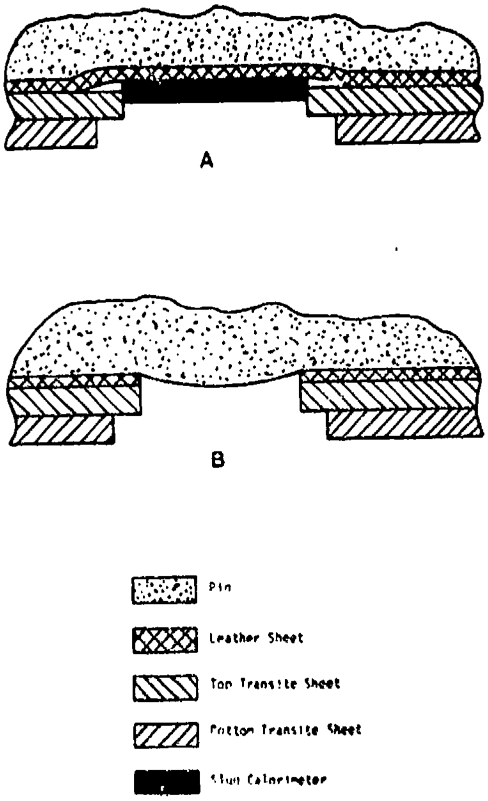

FIGURE 3. Diagram of the Template Test Sites (A) Slug Calorimeter (B) Fabric Configurations.

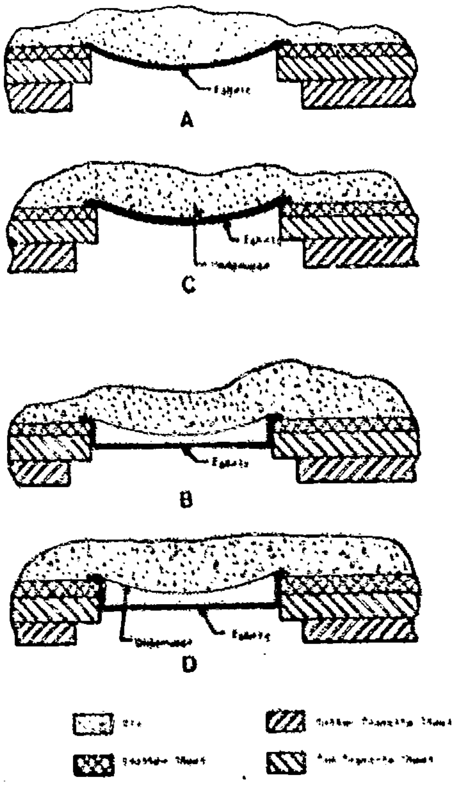

FIGURE 4. Fabric Configuration Groups (A) Group I - A Single Layer in Contact With the Skin; (B) Group II - A Single Layer with a 6.35 mm (One-Fourth Inch) Air Gap Between Fabric and Skin; (C) Group III - Double Layer Design With a Shell Fire Retardant Fabric in Contact With T-Shirt Fabric in Contact With Skin With No Air Gaps; (D) Group IV - Double Layer Design With a 6.35 mm Air Gap Between the Shell Fire Retardant Fabric and the T-Shirt Fabric With the T-Shirt Fabric in Contact With Skin.

TABLE I. FABRIC CHARACTERISTICS.

Fabric	Weave	Weight* (oz/yd^2)	Thickness** (inches)	Air permeability*** (ft^3/ft^2/min.)
Nomex Aramid®	Twill	4.8	.016	181.5
Polybenzimidazole	Twill	4.5	.014	171.0
Exp. High Temp. Polymer (HT4)	Plain	4.8	.010	12.8
New Weave Nomex Aramid®	Plain	4.6	.008	28.1
T-Shirt	Jersey knit	4.8	.023	152.5

*ASTM methods D1910-64, D231-62.
**ASTM method D1777-64.
***ASTM method D737-46.

NOTE: Complete fabric analysis available from authors on request.

TABLE 2

FABRICS BY TREATMENT GROUP AND POSITION OF PIG

GROUP I (IN CONTACT)

A = Standard Air Force Nomex® (AFN)

B = Polybenzimidazole (PBI)

C = Experimental High Temperature Polymer (HT4)

D = New Weave Nomex® (NWN)

E = No Fabric Control

GROUP II (WITH SPACE)

A = AFN/S

B = PBI/S

C = HT4/S

D = NWN/S

E = Control

GROUP III (in contact with T-shirt)

A = AFN/T, i.e., Air Force Nomex with T-shirt

B = PBI/T

C = HT4/T

D = NWN/T

E = Control

GROUP IV (with T-shirt with space)

A = AFN/T/S

B = PBI/T/S

C = HT4/T/S

D = NWN/T/S

E = Control

LAYOUT OF FABRICS BY POSITION ON THE PIG AND WITHIN THE TEMPLATE FOR TREATMENT GROUPS I, II, III, AND IV

	Left Rear	Left Front	Right Rear	Right Front
Pig Site #	1 2 3 4 6	1 2 3 4 6	1 2 3 4 6	1 2 3 4 6
1	A B C D E	B C D E A	C D E A B	D E A B C
2	E A B C D	A B C D E	B C D E A	C D E A B
3	D E A B C	E A B C D	A B C D E	B C D E A
4	C D E A B	D E A B C	E A B C D	A B C D E
5	B C D E A	C D E A B	D E A B C	E A B C D

TABLE 3

GRADING SYSTEM FOR CLINICAL OBSERVATIONS OF THE BURN

Grade	Surface Appearance	Hair Removal	Additional Information	Human Equivalent
1	Normal Skin	Difficult	Pliable & Painful	No Burn
2	Mild Erythema (Pink)	Difficult	Pliable & Painful, Hot	Epidermal
3	Moderate Erythema (Red)	Difficult	Pliable & Painful, Hot	Epidermal
4	Severe Erythema (Dark Red or Purple)	Difficult	Pliable & Painful, Hot	Epidermal
5	Patchy Coagulation: White Crests 10-30%, Red or Purple Valleys 70-80%	Difficult	Pliable & Painful, Hot	Superficial Intradermal
6	White 50% Red or Purple 50%	Difficult	Pliable & Painful, Hot	Superficial Intradermal
7	White 70-80%, Red or Purple 20-30%	Difficult	Pliable & Painful, Hot	Superficial Intradermal
8	Uniform Coagulation: White >90%, Red <10%	Some Difficulty	Less Pliable & Painful, Cool	Deep Intradermal
9	Shiny or Opalescent White	Fairly Easy	Less Pliable & Painful, Cool	Deep Intradermal
10	Dull White or Tan: Dry Looking Surface	Easy	Less Pliable & Painful, Cool	Deep Intradermal
11	Multiple Small Vesicles (<5 mm)	Very Easy	Less Pliable & No Pain, Cool	All Dermal
12	Raised Delicate Blebs	Very Easy	Less Pliable & No Pain, Cool	All Dermal
13	Broken Large Delicate Blebs	Very Easy	Less Pliable & No Pain, Cold	All Dermal
14	Carbonation of Center, Charred Blebs at Periphery	Very Easy but Often Burned Off	Leathery, No Pain, Cold	Subdermal
15	50% Charred, Usually No Blebs Around Periphery	Very Easy but Often Burned Off	Stiff, No Pain, Cold	Subdermal
16	>70% Charred, No Blebs	Burned Off	Hard, No Pain, Cold	Subdermal

TABLE 4
MICRO-GRADE DEFINITIONS[4] [11]

Grade	Definition
0	No thermal damage
1	Cell damage without acidophilism
2	Epidermal acidophilism (partial)
3	Epidermal acidophilism (complete)
4	Dermal-epidermal separation (partial)
5	Dermal-epidermal separation (complete)
6	Dermal superficial <500μ
7	Dermal mid 500-1000μ
8	Dermal deep 1000-1500μ
9	Dermal complete 1500-dermal/adipose border
10	Adipose

RESULTS

From 20 pigs and 400 available burn sites, 371 clinical and 346 microscopic burn grades and 233 burn depths provided acceptable data. Grades and depths were assigned to their respective exposure groups by fabric and fabric configuration, i.e., single or double layer, in contact or spaced away. The mean and standard deviations were calculated for each group. These results are tabulated in Table 5 (page 11) and presented graphically in Figures 5, 6 and 7 (pages 11 and 12). The most severe burns (the ones with the highest grades) were associated with the unprotected control sites while least severe burn grades were found in groups using double layered fabric with the outer fabric spaced 6.35 mm away from the T-shirt inner layer.

TABLE 5

SUMMARY OF BURN GRADES/DEPTHS BY TREATMENT GROUP AND FABRIC

Treatment	Fabric*	Clinical Grade**			Micro-Grade**			Depth**(μ)		
GROUP I	AFN	11.65	1.42	20	7.18	1.01	17	1313	608	15
	PBI	11.74	1.82	19	6.59	0.94	17	903	542	15
	HT4	11.10	1.97	20	7.00	1.24	18	1033	537	13
	NWN	12.30	1.78	20	7.11	0.96	18	1098	519	16
	Control	13.75	1.16	20	7.13	0.83	15	1149	539	14
GROUP II	AFN/S	11.00	2.00	20	7.05	1.61	19	624	544	11
	PBI/S	10.10	1.87	21	6.29	1.06	21	666	624	17
	HT4/S	8.55	1.32	20	5.75	1.12	20	688	485	9
	NWN/S	10.63	2.22	19	6.68	1.16	19	1099	754	13
	Control	14.32	1.42	19	6.82	0.64	17	1138	526	15
GROUP III	AFN/T	8.75	0.55	20	5.30	1.03	20	436	328	13
	PBI/T	9.25	0.72	20	5.35	1.09	20	578	643	15
	HT4/T	8.40	1.50	20	5.06	0.80	18	419	478	6
	NWN/T	9.40	1.54	20	5.58	0.77	19	465	408	10
	Control	14.88	0.33	17	7.67	0.98	15	1326	550	11
GROUP IV	AFN/T/S	8.55	1.64	20	5.84	1.34	19	496	336	13
	PBI/T/S	7.07	2.22	15	5.40	0.91	15	356	413	8
	HT4/T/S	5.60	2.27	10	4.70	1.06	10	225	169	5
	NWN/T/S	8.50	1.61	14	5.62	0.77	13	356	100	6
	Control	15.00	0.00	17	8.44	1.41	16	1214	539	8

*-/S = with space; -/T = with T-shirt; -/T/S = with T-shirt and space
**mean ± 1 S.D., Number of Observations

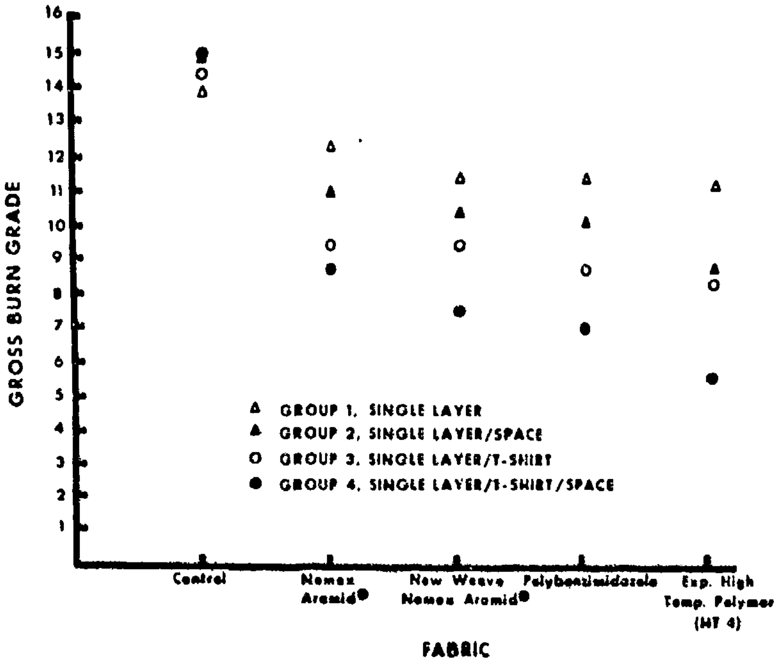

FIGURE 5. Mean Clinical (Gross) Grade for Each Fabric/Configuration.

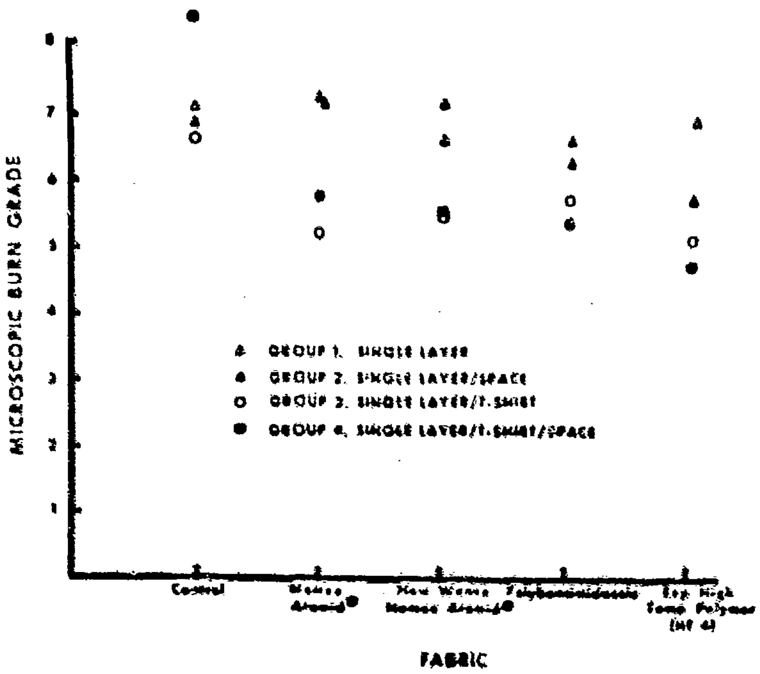

FIGURE 6. Mean Histopathological Microscopic Grade for Each Fabric/Configuration.

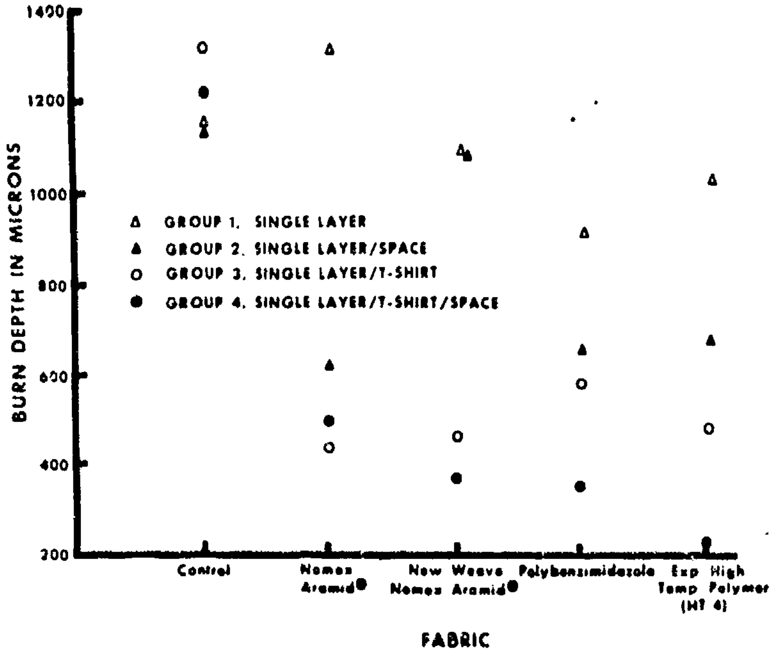

FIGURE 7. Mean Depth of Burn in Microns for Each Fabric/ Configuration.

An analysis of variance and an analysis of covariance were performed using the control burn grades as a function of position with heat flux as the covariate to test the validity of the assumption of uniform flux. Table 6 (page 13) summarizes the results of this analysis of variance. Position and heat flux were not significant variables; therefore, they were eliminated as variables from the subsequent analysis.

An analysis of variance (Table 7, page 14) showed that the controls by Group were significantly different ($p < 0.01$) for both microgrades and gross grades. The burn depths were not significant.

Examination of the data obtained from the sites which were completely unprotected from the fire showed some variation in the histopathological and in the gross evaluation scores, although there was no significant variation in measured burn depth (Table 7, page 14). The experimental design permits comparison of the effect of each fabric and each fabric configuration with all other fabrics and configurations tested. It is much more sensitive and specific to compare each with each other directly by the methods of analysis of variance. This was done, and the results of a modified Newman-Keuls' multirange test are summarized in Table 8 (page 15). In this test, means were arranged in ascending order, and lines were drawn beneath those treatment means which were not significant at $p < 0.05$. Means not overlapped by the same line were significantly different at $p < 0.05$.

TABLE 6

CONTROL BURN GRADES AND DEPTHS BY TEMPLATE POSITION

Position	Micro*			Gross*			Depth*(μ)		
1	7.73	1.35	11	14.23	1.24	13	756	548	6
2	7.64	1.28	14	14.67	0.62	15	1444	345	10
3	7.43	1.34	14	14.57	0.76	14	1122	723	12
4	7.23	0.73	13	14.50	0.97	16	1323	258	11
5	----------------SLUG CALORIMETER----------------								
6	7.55	1.13	11	14.27	1.58	15	1163	537	9
**ANOVA F	0.33			0.44			1.99		
***COANOVA F	0.27			0.44			1.26		

No Significant F Ratios

*mean ± 1 S.D., Number of Observations
**Analysis of variance
***Analysis of covariance with heat flux as the covariate

TABLE 7

CONTROL BURN GRADES AND DEPTHS BY TREATMENT GROUP

Group	Clinical**			Micro**			Depth*(μ)		
I	13.75	1.16	(20)	7.13	0.83	(15)	1149	539	(14)
II	14.32	1.42	(19)	6.82	0.64	(17)	1138	526	(15)
III	14.88	0.33	(17)	7.67	0.98	(15)	1326	556	(11)
IV	15.00	0.00	(17)	8.44	1.41	(16)	1214	539	(8)
ANOVA F	6.67**			8.03**			0.31		
COANOVA F	6.25**			7.81**			0.21		

*Mean ± 1 S.D., Number of Observations ( )

**Significant at $p < .01$

TABLE 8

CLINICAL GRADE

HT4 TS	PBI TS	HT4 T	HT4 S	NWN TS	AFN TS	AFN T	PBI T	NWN T	PBI S	NWN S	AFN S	HT4	AFN	PBI	NWN
———															
	———														
		———	———	———	———	———	———	———							
							———	———	———						
									———	———	———	———			
										———	———	———	———		
											———	———	———	———	
													———	———	———

MICRO GRADE

HT4 TS	HT4 T	AFN T	PBI T	PBI TS	NWN T	NWN TS	HT4 S	AFN TS	PBI S	PBI	NWN S	HT4	AFN S	NWN	AFN
———	———	———	———	———											
	———	———	———	———	———	———									
		———	———	———	———	———	———	———							
					———	———	———	———	———						
								———	———	———					
									———	———	———				
										———	———	———	———	———	———

DEPTH

HT4 TS	NWN TS	PBI TS	HT4 T	AFN T	NWN T	AFN TS	PBI T	AFN S	PBI S	HT4 S	PBI	HT4	NWN	NWN S	AFN
———	———	———	———	———	———	———	———	———	———	———					
			———	———	———	———	———	———	———	———	———				
								———	———	———	———	———			
										———	———	———	———	———	
												———	———	———	———

COMBINED RANK

1															16
HT4 TS	HT4 T	PBI TS	NWN TS	AFN T	PBI T	NWN T	AFN TS	HT4 S	PBI S	AFN S	NWN S	PBI	HT4	NWN	AFN

NOTE: All grades not overlapped by the same line are significantly different at $p < 0.05$

DISCUSSION

Moritz and Henriques[13] have described porcine skin before and after thermal exposures and compared it to human skin burns, showing the relative vulnerability of porcine and human skin to thermal injury. They found little or no quantitative difference in the susceptibility of human and porcine epidermis to thermal injury at similar surface temperatures. Moritz[14] delineated the pathogenesis and pathological characteristics of cutaneous burns in relation to the duration and intensity of thermal exposure and to the susceptibility to organization, repair, and healing.

Perkins, Pearse, and Kingsley[15] demonstrated comparative surface appearance for similar threshold values (cal/cm^2) for human and porcine skin subjected to radiant energy in epidermal and intradermal (and perhaps subdermal) burn lesions. Their data were comparable to the values of 2 cal/cm^2 for epidermal burns and 3.5 cal/cm^2 for deep intradermal burns in humans reported by Butterfield and Dixey[16] and correlated well with the 3.9 cal/cm^2/sec (0.54 sec exposure) value for subdermal human burns reported by Moncrief.[17]

The heat capacities and thermal conductivities of cutaneous and subcutaneous tissues of the pig, in vivo observations of caloric uptake of pigskin, rise in temperature at the dermis-fat interface as a function of both time and skin surface temperature, and an estimation of the temperature changes at the epidermal-dermal interface during the exposure of the skin surface to heat have been reported.[18] Moritz, et al,[19] have investigated the mechanisms by which thermal exposures, in which heat was transferred to the body through an envelope of air, cause disability and death.

Comparative studies of the skin of the domestic pig and human have been reported by Montagna and Yun.[20] They noted that the skin of the pig shares anatomical and histochemical features with that of man, although some dissimilarities exist.

Pigskin, like most animal models, is not perfect, but the weight of evidence on similarity of structure, comparability of burn damage, reaction of pigs as models for human burn shock[21] and consistency of data obtained in testing lightweight underwear[8] argue in favor of using pigskin as the animal model of choice in a bioassay method for determining the thermal protective capability of fabrics.

An extensive review of the methods for simulating postcrash fire led to a proposal to use a new field fire simulation cell for testing whole flight garments.[1] However, this device is not practical for testing candidate fabrics using the bioassay method. The flame gun used in an earlier study suffered from an imbalance in radiative and convective heating compared to naturally occurring postcrash fires.[7] A method was needed which would more accurately duplicate the highly radiative nature (70 to 90%) of postcrash fires. Moreover, the chemical environment within the fire may be important in some circumstances in contributing to fabric failure; so, for this study, JP-4 fuel was used since it is standard for Army helicopters.

A survey of the available thermal sources such as Meeker burners, quartz lamps, carbon arc lamps, and small pool fires led to the choice of a NASA designed furnace which does burn JP-4 fuel. When the furnace is at steady-state, the hot furnace wall simulates the radiation background of a field fire while the rich burning JP-4 fuel adds the convective and chemical environments.[2]

The five-second exposure time was chosen based on the results of a pilot experiment using one-, three-, five-, and seven-second exposures.[4] The objective was to choose an exposure time which would result in deep dermal control burns.

The four methods of applying the fabrics to the skin were selected to simulate the ways in which various segments of a flight suit relate to a pilot's skin. This, of course, does not explore all the possibilities since, for example, double layers of outer shell fabric, zippers, and the like were not included.

As expected, fabrics attenuated the thermal damage by varying amounts depending on the fabric type and method of application. Double layers, especially those with air space between the layers, showed the greatest degree of protection. This confirms earlier data of Stoll,[6] Stanton,[22] Knox,[8] Berkley,[23] and Mixter.[24]

Of the various fabric types, Fabric HT4 gave more protection in each method of application than did any other fabric. However, it was only statistically significantly different from all others in the double-layered, spaced-away configuration (Group IV, HT4/T/S).

What, then, may be concluded from these observations? Under the conditions of this study there appears to be no clear choice among the fabrics evaluated. HT4, while slightly better in attenuating heat flux, does not provide a significant increase in clinically significant protection. For example, consider the burn depths in Table 5 (page 10). Within each group the data are clustered, and the only clear improvement in protection comes as a result of adding double layers and air gaps. To be clinically significant a new fabric or uniform design must clearly lower morbidity. If, however, all the candidate fabrics fail to prevent burns in a given test, it raises several questions. First, was the test unreasonably severe? This would not appear to be the case, since the experimental conditions fit quantitatively within the known physical properties of actual postcrash fires. Second, were the methods of application reasonable? Here again the methods were chosen to simulate actual operational flight clothing use. Finally, is there such a thing as an acceptable burn? The ideal is clearly no burn at all. However, given the trade-offs which must be made in designing an acceptable flight suit, the ideal could probably only be achieved by entirely preventing the postcrash fire.

Given the reality of the occurrence of postcrash fires and the state of the art in flight clothing design, there will be burns. Decisions on new fabrics must take into account the available clinical data which relate age, sex, degree and area of burn, and survivability. For instance, an improvement of several hundred microns in burn depth would result in a corresponding increase in survivability. It is an increase in survivability which must be weighed against the cost and acceptability of a new flight garment. To predict survivability, however, one also needs to know the area burned in addition to the degree. This information is most readily obtained with properly designed and appropriately instrumented manikins subjected to full scale fires.

The study reported here emphasizes the general effectiveness of multiple layers and suggests that improvement can be achieved by redesign of present uniforms using multiple layers and present stocks of Nomex® and/or new weave Nomex® rather than going to new fiber types. This course is particularly prudent in the rotary-wing environment where installation of crashworthy fuel cells and newer crashworthy designs have resulted in reducing the threat of fire or fire induced injury.[35]

Finally, it is difficult to evaluate fabric performance fully with a one point test in which only one heat flux and one exposure duration are used. Thermal protection and ultimate failure are a complex, dynamic process, and until understanding of that process improves, a one point test (especially, if pass/fail) is inadequate.

CONCLUSIONS

All fabrics evaluated provided some protection.

Multiple layers and fabric spacing are important factors in increasing the level of protection.

Fabric HT4 consistently gave the best protection, but this increased protection was not of clinical significance.

REFERENCES

1. Albright, J. D., Knox, F. S., III, DuBois, D. R., and Keiser, G. M. "The testing of thermal protective clothing in a reproducible fuel fire environment, a feasibility study" (USAARL Report No. 71-24). Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory, June 1971.

2. Knox, F. S., et al. "A fire simulator/shutter system for testing protective fabrics and calibrating thermal sensors" (USAARL Report No. 79-3). Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory, March 1979.

3. Department of the Army Approved Small Development Requirement (SDR) for Clothing System for Army Aircrewmembers. Paragraph 26(2), February 9, 1966.

4. Knox, F. S., III, McCahan, G. R., Jr., and Wachtel, T. L. Use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. Aerospace Medicine 45(8): 933-938, 1974.

5. McCoy, J. A., Micks, D. W., and Lynch, J. B. Discriminant function probability model for predicting survival in burned patients. JAMA 203: 644-646, 1968.

6. Stoll, A. M., and Chianta, M. A. "Heat transfer through fabrics" (NADC-MR-7017). Warminster, PA: Department of the Navy, Naval Air Development Center, Aerospace Medical Department, September 16, 1970.

7. Knox, F. S., III, Wachtel, T. L., and Knapp, S. C. "Mathematical models of skin burns induced by simulated postcrash fires as aids in thermal protective clothing design and selection" (USAARL Report No. 78-15). Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory, June 1978.

8. Knox, F. S., III, McCahan, G. R., Jr., Wachtel, T. L., Trevethan, W. P., Martin, A. S., DuBois, D. R., and Keiser, G. M. "Engineering test of lightweight underwear of the winter flight clothing system: Thermal protection" (USAARL Report No. 71-19). Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory, June 1971.

9. Ragan, H. A., and Gillis, M. F. Restraint, venipuncture, endotracheal intubation and anesthesia of the miniature swine. Laboratory Animal Science 25: 409 & 419, 1975.

10. Wachtel, T. L., McCahan, G. R., Jr., and Knox, F. S., III. Methods of preparing porcine skin for bioassay of thermal injury. Military Medicine 141: 536, 1977.

11. Wachtel, T. L., Knox, F. S., III, and McCahan, G. R., Jr. "A porcine bioassay method for analysis of thermal protective fabrics: A clinical grading system" (USAARL Report No. 78-8). Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory, June 1978.

12. Lyon, J. L., Davis, T. P., and Pearse, H. E. "Studies of flash burns: The relationship of thermal energy applied and exposure time to burn severity" (University of Rochester Report 394, Atomic Energy Report). Rochester, NY: University of Rochester, May 1955.

13. Moritz, A. R., and Henriques, F. C. Studies of thermal injury. II. The relative importance of time and surface temperature in the causation of cutaneous burns. American Journal of Pathology 23: 695-720, 1947.

14. Moritz, A. R. Studies of thermal injury. III. The pathology and pathogenesis of cutaneous burns, an experimental study. American Journal of Pathology 23: 915-941, November 1947.

15. Perkins, J. B., Pearse, H. E., and Kingsley, H. D. "Studies on flash burns: The relation of the time and intensity of applied thermal energy to the severity of burns" (Atomic Energy Report UR 217). Rochester, NY: University of Rochester, 1952.

16. Butterfield, W. S. H., and Dixey, J. R. B. Burns from atomic bombs. J. Roy. Nav. Med. Sci. 37: 9, 1951.

17. Moncrief, J. A. Burns. Principles of Surgery. Ed. S. I. Schwartz. New York, NY: McGraw-Hill, Inc., pp. 205-206, 1969.

18. Henriques, F. C., and Moritz, A. R. Studies of thermal injury. I. The conduction of heat to and through skin and the temperatures attained therein. A theoretical and an experimental investigation. American Journal of Pathology 23: 531-549, 1947.

19. Moritz, A. R., Henriques, F. C., Dutra, F. R., and Weisiger, J. R. Studies of thermal injury. IV. An exploration of the casualty-producing attributes of conflagration. Archives of Pathology 43: 466-488, 1947.

20. Montagna, W., and Yun, J. S. The skin of the domestic pig. J. Int. Coll. Surg. 42: 11-21, July 1964.

21. Wachtel, T. L., McCahan, G. R., Jr., and Monafo, W. W., Jr. Fluid resuscitation in a porcine burn shock model. Journal of Surgical Research 23: 405-414, 1977.

22. Stanton, R. M. "Heat transfer and flammability of fibrous materials" (AFML-TR-70-230). February 1971.

23. Berkley, K. M. "The effect of air space on sub-fabric burns in swine" (Atomic Energy Project UR 490). Rochester, NY: The University of Rochester, June 14, 1957.

24. Mixter, G., and Pearse, H. E. "Studies of flash burns: The protection afforded by 2, 4 and 6 layer fabric combinations" (Atomic Energy Project UR 261). Rochester, NY: The University of Rochester, June 4, 1953.

25. Knapp, S. C., Allemond, P. A., and Karney, D. H. Helicopter crashworthy fuel systems and their effectiveness in preventing thermal injury. AGARD Conference Proceedings No. 255, pp. 61-1 - 61-7, May 1978.

DISTRIBUTION LIST FOR USAARL REPORTS

Defense Documentation Center
Alexandria, VA 22314 (12)

Director of Defense, Research and Engineering
ATTN: Assistant Director (Environmental & Life Sciences)
Washington, DC 20301 (1)

Uniformed Services University of the Health Sciences
4301 Jones Bridge Road
Bethesda, MD 20014 (1)

Commander
US Army Medical Research and Development Command
ATTN: SGRD-AJ (Mrs. Madigan)
Fort Detrick
Frederick, MD 21701 (5)

Redstone Scientific Information Center
DRDMI-TBD
US Army Missile R&D Command
Redstone Arsenal, AL 35809 (1)

US Army Yuma Proving Ground
Technical Library
Yuma, AZ 85364 (1)

US Army Aviation Engineering Flight Activity
ATTN: DAVTE-M (Technical Library)
Edwards AFB, CA 93523 (1)

US Army Combat Developments Experimentation Command
Technical Library
HQ, USACDEC
Box 22
Fort Ord, CA 93941 (1)

Aeromechanics Laboratory
US Army Research & Technology Labs
Ames Research Center, M/S 215-1
Moffett Field, CA 94035 (1)

Sixth United States Army
ATTN: SMA
Presidio of San Francisco,
California 94129 (1)

Director
Army Audiology & Speech Center
Walter Reed Army Medical Center
Forest Glen Section, Bldg 156
Washington, DC 20012 (1)

US Army Materiel Command
Harry Diamond Laboratories
Scientific & Technical Information Offices
2800 Powder Mill Road
Adelphi, MD 20783 (1)

US Army Ordnance Center & School
Library, Bldg 3071
ATTN: ATSL-DOSL
Aberdeen Proving Ground, MD 21005 (1)

US Army Environmental Hygiene Agency
Library, Bldg E2100
Aberdeen Proving Ground, MD 21010 (1)

Technical Library
Chemical Systems Laboratory
Aberdeen Proving Ground, MD 21010 (1)

US Army Materiel Systems
Analysis Agency
ATTN: Reports Distribution
Aberdeen Proving Ground, MD
21005 (1)

Director
Biomedical Laboratory
Aberdeen Proving Ground, MD
21010 (1)

HQ, First United States Army
ATTN: AFKA-MD (Surgeon's Ofc)
Fort George G. Meade, MD 20755
(1)

Director
Ballistic Research Laboratory
ATTN: DRDAR-TSB-S (STINFO)
Aberdeen Proving Ground, MD
21005 (2)

US Army Research & Development
Technical Support Agency
Fort Monmouth, NJ 07703 (1)

CDR/DIR
US Army Combat Surveillance &
Target Acquisition Laboratory
ATTN: DELCS-D
Fort Monmouth, NJ 07703 (1)

US Army Avionics R&D Activity
ATTN: DAVAA-O
Fort Monmouth, NJ 07703 (1)

US Army White Sands Missile Range
Technical Library Division
White Sands Missile Range
New Mexico 88002 (1)

Chief
Benet Weapons Laboratory
LCWSL, USA ARRADCOM
ATTN: DRDAR-LCB-TL
Watervliet Arsenal
Watervliet, NY 12189 (1)

US Army Research & Technology Labs
Propulsion Laboratory MS 77-5
NASA Lewis Research Center
Cleveland, OH 44135 (1)

US Army Field Artillery School
Library
Snow Hall, Room 16
Fort Sill, OK 73503 (1)

US Army Dugway Proving Ground
Technical Library
Bldg 5330
Dugway, UT 84022 (1)

US Army Materiel Development &
Readiness Command
ATTN: DRCSG
5001 Eisenhower Avenue
Alexandria, VA 22333 (1)

US Army Foreign Science & Technology
Center
ATTN: DRXST-IS1
220 7th St., NE
Charlottesville, VA 22901 (1)

US Army Training & Doctrine Command
ATTN: ATCD
Fort Monroe, VA 23651 (2)

Commander
US Army Training & Doctrine Command
ATTN: Surgeon
Fort Monroe, VA 23651 (1)

US Army Research & Technology Labs
Structures Laboratory Library
NASA Langley Research Center
Mail Stop 266
Hampton, VA 23665 (1)

Commander
10th Medical Laboratory
ATTN: DEHE (Audiologist)
APO New York 09180 (1)

Commander
US Army Natick R&D Command
ATTN: Technical Librarian
Natick, MA 01760 (1)

Commander
US Army Troop Support & Aviation
Materiel Readiness Command
ATTN: DRSTS-W
St. Louis, MO 63102 (1)

Commander
US Army Aviation R&D Command
ATTN: DRDAV-E
P. O. Box 209
St. Louis, MO 63166 (1)

Director
US Army Human Engineering
Laboratory
ATTN: Technical Library
Aberdeen Proving Ground, MD
21005 (1)

Commander
US Army Aviation Research &
Development Command
ATTN: Library
P. O. Box 209
St. Louis, MO 63166 (1)

Commander
US Army Health Services Command
ATTN: Library
Fort Sam Houston, TX 78234 (1)

Commander
US Army Academy of Health Sciences
ATTN: Library
Fort Sam Houston, TX 78234 (1)

Commander
US Army Airmobility Laboratory
ATTN: Library
Fort Eustis, VA 23601 (1)

Air University Library (AUL/LSE)
Maxwell AFB, AL 36112 (1)

US Air Force Flight Test Center
Technical Library, Stop 238
Edwards AFB, CA 93523 (1)

US Air Force Armament Development
& Test Center
Technical Library
Eglin AFB, FL 32542 (1)

US Air Force Institute of Technology
(AFIT/LDE)
Bldg 640, Area B
Wright-Patterson AFB, OH 45433 (1)

US Air Force Aerospace Medical
Division
School of Aerospace Medicine
Aeromedical Library/TSK-4
Brooks AFB, TX 78235 (1)

Director of Professional Services
Office of The Surgeon General
Department of the Air Force
Washington, DC 20314 (1)

Human Engineering Division
6570th Aerospace Medical Research
Laboratory
ATTN: Technical Librarian
Wright-Patterson AFB, OH 45413 (1)

US Navy
Naval Weapons Center
Technical Library Division
Code 2333
China Lake, CA 93555 (1)

US Navy
Naval Aerospace Medical Institute
Library
Bldg 1953, Code 012
Pensacola, FL 32508 (1)

US Navy
Naval Submarine Medical Research
Lab
Medical Library, Naval Submarine
Base
Box 900
Groton, CT 06340 (1)

Director
Naval Biosciences Laboratory
Naval Supply Center, Bldg 844
Oakland, CA 94625 (1)

Naval Air Systems Command
ATTN: V/STOL Aircraft Branch
Department of the Navy
Washington, DC 20360 (1)

US Navy
Naval Research Laboratory Library
Code 1433
Washington, DC 20375 (1)

US Navy
Naval Air Development Center
Technical Information Division
Technical Support Department
Warminster, PA 18974 (1)

Human Factors Engineering Division
Aircraft & Crew Systems Technology
Directorate
Naval Air Development Center
Warminster, PA 18974 (1)

US Navy
Naval Research Laboratory Library
Shock & Vibration Information Center
Code 8404
Washington, DC 20375 (1)

Director of Biological & Medical
Sciences Division
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217 (1)

Commanding Officer
Naval Medical R&D Command
National Naval Medical Center
Bethesda, MD 20014 (1)

Commander
Naval Aeromedical Research
Laboratory Detachment
P. O. Box 29407
Michoud Station
New Orleans, LA 70129 (1)

Federal Aviation Administration
Office of Aviation Medicine
Civil Aeromedical Institute
ATTN: Library
Oklahoma City, OK 73101 (1)

Department of Defence
R.A.N. Research Laboratory
P. O. Box 706
Darlinghurst, N.S.W. 2010
Australia (1)

FORT RUCKER DISTRIBUTION

Commander
US Army Aviation Center and
Fort Rucker
ATTN: ATZQ-CDR
Bldg 114 (1)

Commander
US Army Aviation Center and
Fort Rucker
ATTN: ATZQ-T-ATL
Bldg 5907 (1)

Chief
US Army Research Institute Field
Unit
Bldg 501 (1)

Director
Directorate of Combat Developments
Bldg 507 (1)

Commander
US Army Aeromedical Center
Bldg 301 (3)

Commander
US Army Safety Center
Bldg 4905 (1)

Director
Directorate of Training Developments
Bldg 502 (1)

President
US Army Aviation Board
Cairns AAF, Bldg 501AB (1)

Commander
US Army Aircraft Development Test
Activity
Cairns AAF, Bldg 30601 (1)