AEROSPACE REPORT NO.
ATR-75(7906)-1, VOL. II

EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

FINAL REPORT

PROTECTIVE ARMOR DEVELOPMENT PROGRAM

Volume II - Technical Discussion

Prepared for

National Institute of Law Enforcement and Criminal Justice
LAW ENFORCEMENT ASSISTANCE ADMINISTRATION
U.S. DEPARTMENT OF JUSTICE

The Aerospace Corporation

Report No.
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VOLUME II — TECHNICAL DISCUSSION

Law Enforcement Development Group
THE AEROSPACE CORPORATION
El Segundo, California

December 1974

Prepared for

National Institute of Law Enforcement
and Criminal Justice
LAW ENFORCEMENT ASSISTANCE ADMINISTRATION
U.S. DEPARTMENT OF JUSTICE

Contract No. J-LEAA-025-73

This project was supported by Contract Number J-LEAA-025-73 awarded by the Law Enforcement Assistance Administration, U.S. Department of Justice, under the Omnibus Crime Control and Safe Streets Act of 1968, as amended. Points of view or opinions stated in this document are those of the authors and do not necessarily represent the official position or policies of the U.S. Department of Justice.

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Approved

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Law Enforcement and Telecommunications
Division

ABSTRACT

This report summarizes the results of a multiagency effort, funded by the Law Enforcement Assistance Administration for the development of lightweight, inconspicuous body armor to protect law enforcement personnel. The overall activity included identifying operational requirements, conducting ballistic tests, assessing a variety of candidate materials, performing medical assessments, investigating the mechanics of bullet penetration, and subjecting selected materials to environmental testing.

The program emphasized development of a number of protective garment styles, namely, undershirts, sport jackets, and uniform components. Prototype garments were produced and successfully tested for wearability. These garments weigh less than half that of commercially available nylon protective garments and are capable of stopping a .38 caliber bullet fired at close range. The initial test results indicate that such lightweight protective garments can be worn for routine patrol operations during most of the year.

Plans are also discussed for extensive field tests of a variety of these garments under a wide range of field conditions.

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PREFACE

This report is divided into three parts: Executive Summary (Volume I), Technical Discussion (Volume II), and Appendices (Volume III).

The Executive Summary volume presents a brief, concise review of the activities on the Protective Armor Development Program during FY 73 and FY 74, and summarizes the principal conclusions and recommendations. The purpose of Volume I is to provide a condensed, easily assimilated overview of the program effort and the progress achieved.

This volume, Volume II--Technical Discussion, is the principal part of the series. It provides a comprehensive discussion of the program objectives, operational requirements, and ground rules, as well as detailed descriptions of protective garment development and wearability test activities. Much of the material is based on more detailed inputs from both The Aerospace Corporation and subcontracted sources.

Some of the backup material used in this volume is presented as Volume III--Appendices of this report. Although some appendices have been published previously, they have been included in the interests of completeness and ease of reference.

ACKNOWLEDGMENTS

The development phase of the Protective Armor program received support from numerous agencies and many individuals. Contributions were made by the MITRE Corporation, National Bureau of Standards, U.S. Army's Edgewood Arsenal and Natick Laboratory, Lawrence Livermore Laboratory, DuPont, independent consultants, various armor and garment manufacturers, numerous law enforcement units, and several federal agencies. The effort was funded and directed by the National Institute of Law Enforcement and Criminal Justice with appreciated specific guidance provided by Messrs. Joe Kochanski, George Shollenberger, and Lester Shubin of the Institute. Dr. John Benfield of the UCLA Medical School provided valuable medical consulation, and Dr. Paul Blatz of Shock Hydrodynamics provided technical support to The Aerospace Corporation on the Kevlar materials research reported herein. Special acknowledgment is made to the personnel of the Materials Science Laboratory of The Aerospace Corporation for the pioneering experimental test work performed with Kevlar.

The principal participants in this study from The Aerospace Corporation were:

R. P. Kennel – Program Director

L. G. King – Project Manager

The additional contributions made by the following members of The Aerospace Corporation technical staff are gratefully acknowledged:

T.H. Davey	— Operations Requirements
R.A. Merkle	— Assault Statistics; Field Evaluation Planning
R.W. Fillers	— Material Laboratory Testing
J.F. Ward	— Material Environmental Testing; Garment Design
R.V. Cox	— Wearability Testing

Finally, the support of E. Perchonok in organizing the contents of this report, integrating the results of the diverse supporting activities, and directing report preparation is gratefully acknowledged.

CHAPTER I. INTRODUCTION

As part of its Equipment Systems Improvement Program, the National Institute of Law Enforcement and Criminal Justice (NILECJ) of the Law Enforcement Assistance Administration (LEAA) initiated a program during FY 1973 to encourage the development of lightweight protective garments for use by law enforcement personnel and public officials.

In the past, body armor has been generally developed for military applications and then adapted to civilian use. Such armor is usually heavy and conspicuous, and it is often not worn unless an immediate danger is foreseen. Two general types of armor have been developed for the military: hard-faced armor (steels or ceramics) backed by fiber laminates for stopping high-velocity projectiles, and soft-material armor (nylons) for stopping shrapnel. The civilian application of such protective armors, although increasing, is still not widespread among law enforcement personnel, and the number of police assault fatalities is growing every year.

The primary reason for the limited use of body armor by law enforcement personnel during routine patrol operations is the discomfort and conspicuousness of currently available, commercial protective garments. If these disadvantages were to be eliminated, or at least reduced, wider acceptance of such garments for law enforcement applications should result. Accordingly, in September 1972, at the request of NILECJ, the Aerospace Corporation in conjunction with several U.S. Army laboratories initiated a program to develop lightweight protective inner and outer garments to meet this existing need.

I.

The overall program objectives were:

- To support the development of comfortable, inconspicuous, lightweight, continuous wear garments capable of providing protection against common handguns
- To demonstrate adequate user protection
- To encourage user acceptance
- To disseminate the technology acquired among both potential users and industry.

It was recognized that complete protection, especially in the head area, was not immediately practical; therefore, program effort was focused primarily on protection of the torso. It was also recognized that both extensive user and industry participation would be needed. A broad spectrum of program participants was augmented by frequent consultations with law enforcement agencies and synthetic yarn and garment manufacturers. The law enforcement agencies offered garment and style recommendations and participated in prototype garment field evaluation. The industry supported materials and yarn technology and development, weaving of the protective cloth, and designing and fabricating garments.

The key organizations participating in the program and the function and responsibility of each were as follows:

Advanced Technology Division (NILECJ) - overall program control and management

MITRE Corporation - preliminary operational requirements

National Bureau of Standards - test standards and guidelines; anthropomorphic data

U.S. Army Laboratories (Edgewood Arsenal and Natick) - detailed material, ballistic, and medical testing; garment development

The Aerospace Corporation - program technical integration; development subcontracting; laboratory testing; field evaluation

In addition to its in-house activity, The Aerospace Corporation secured the support of the Lawrence Livermore Laboratory of the Atomic Energy Commission. The Lawrence Livermore Laboratory had previously done ballistic testing and analysis for the U.S. Army and had a capability for assessing bullet/garment/wearer interactions.

Program effort was divided into two phases: feasibility assessment and garment development. The initial phase was devoted to assessing the feasibility of developing improved, lightweight, protective garments. Specific activities included an assessment of the threat against which protection is desired, identification of operational requirements, ballistic testing of candidate materials and fabrics, and an initial evaluation of the "blunt trauma" damage to the body behind the protective armor.[1]

The second phase was initiated in FY 74 and was devoted to developing and testing a variety of protective garments, additional blunt trauma investigation, laboratory studies of the ballistic protection process, and environmental testing of the selected protective material. A schedule for the second phase activities and the participants involved is shown in Figure 1.

I.

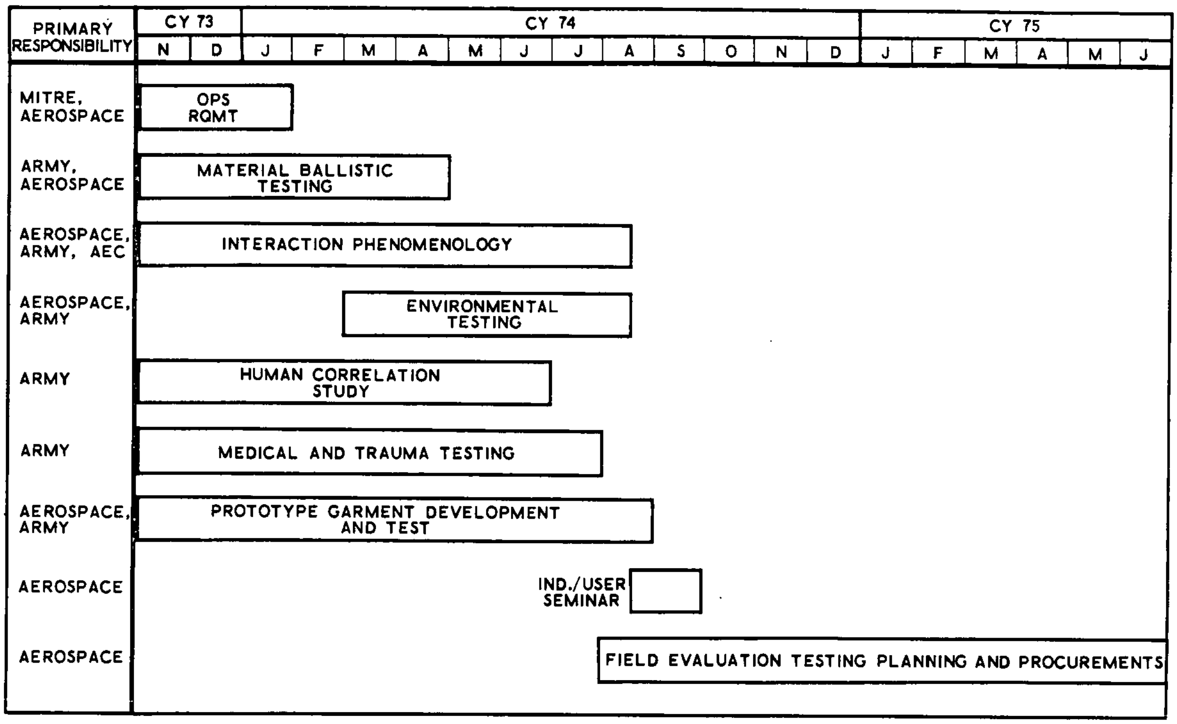


Figure 1. Development and Test Schedule

An industry/user seminar that summarized the development and test results was held at the end of the second phase. This seminar was part of the technology transfer process and is discussed in detail in Appendix A of this volume. A data package,[2] was prepared and distributed to the seminar attendees.

The results of the Protective Armor Development Program are presented in this three-volume report:

Volume I - Executive Summary

Volume II - Technical Discussion

Volume III - Appendices

A companion report on the details of the support provided by the U.S. Army laboratories is being published separately by that agency.

In this document, Volume II, the technical results from both the feasibility assessment and garment development phases of the program are discussed. In addition, plans are presented for intended field tests of a variety of improved protective garments over a wide range of field conditions.

CHAPTER II. APPROACH

When a protective garment intercepts a bullet directed at the wearer, the dissipation of the kinetic energy of the bullet is divided among several phenomena, including bullet deformation, interaction with and deformation of the protective garment, and interaction with and deformation of the body of the wearer. In addition, some momentum transfer occurs between the bullet and the body, which causes a rearward displacement of the body. In order to properly design body armor, especially lightweight garments, it is important to understand these phenomena, their interaction, and how they are influenced by the various garment design parameters.

Past body armor developments, although cognizant of these phenomena, have usually been based on experimental procedures and a somewhat brute force approach. Little was done to provide analytic support for developing an understanding of the physical processes involved, to establish the characteristics of optimum materials and garment designs, or to plan and implement a systematic program for experimentally evaluating the parameters involved and establishing desirable protective garment design trends.

It was the intent of this program to combine both analytic and experimental procedures into a systematic approach to lightweight protective garment development by acquiring a better understanding of the processes involved in protecting the wearer, incorporating those processes in garment designs, and then undertaking wearability and field tests of prototype garments. Program elements included the following major activities:

- Threat assessment and operational requirements
- Physical parameters of the protective process
- User wearability tests
- Field tests

A brief description of the effort devoted to date to each of these program elements is presented in the paragraphs that follow.

A. Threat Assessment and Operational Requirements

Data on firearm assault on law enforcement officers were collected and examined. In addition, the types and distribution of confiscated weapons were analyzed. Data were also assembled and assessed on the number of assault fatalities and the proportion of torso wounds. This information served to indicate which type of weapon represented the greatest threat and the benefits available by using a lightweight protective garment capable of being routinely worn by law enforcement personnel.

Information was also acquired from various law enforcement agencies on the types of garments for which ballistic protection is desirable and the conditions of use and wear to which such garments are exposed. This information was combined with the threat assessment to provide the basis for the operational requirements used in guiding the program.

B. Physical Parameters of the Protective Process

Acquiring a better understanding of the complex processes involved in protecting the wearer of a lightweight protective garment requires examination of numerous other factors in addition to the threat. As indicated in Figure 2, the nonpenetrating dynamics provided by the protecting fabric, the body loading, and blunt trauma (damage to internal body organs) must all be considered in evaluating the effectiveness of such armor.

Program activity included an assessment of each of these factors. In addition, an assessment was made of the interaction among these factors in absorbing the kinetic energy and momentum of the bullet and preventing penetration and serious medical injury. Both analytical activities and experimental laboratory effort were involved in this phase of the program.

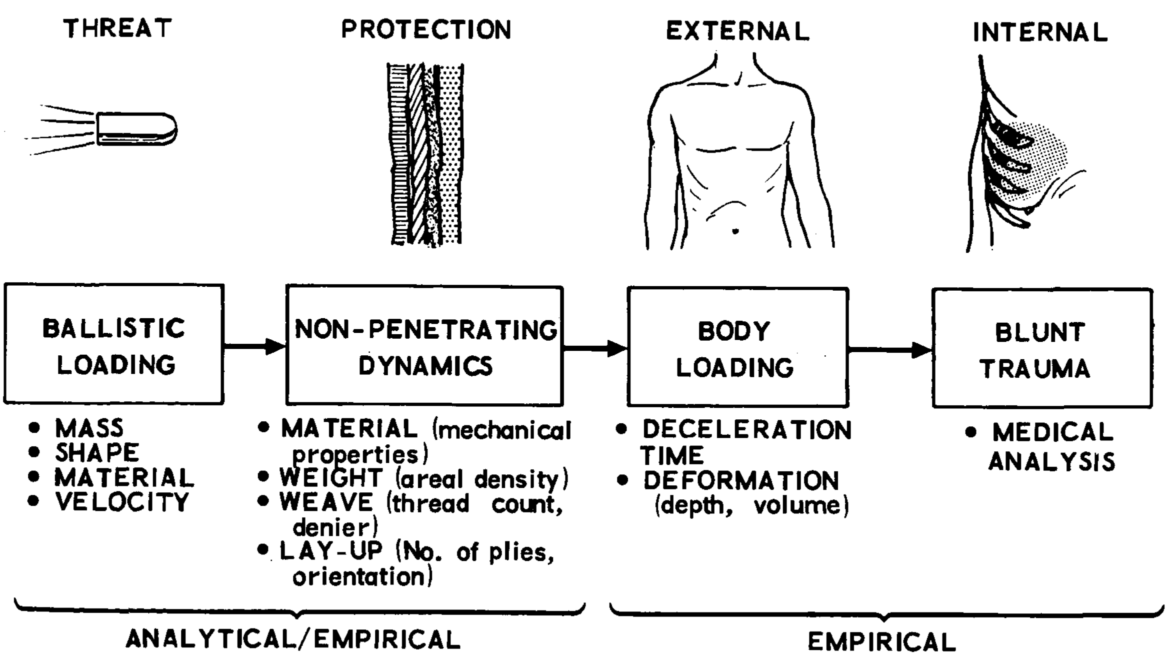


Figure 2. Factors Involved in Establishing Body Armor Effectiveness

C. User Wearability Testing

With the background acquired during the initial phases of the program, prototype garments were designed and fabricated. Several garment types, including undershirts, sport jackets, and elements of police uniforms, were provided to several law enforcement departments for user reaction and wearability assessment.

The purpose of this phase of the program was to uncover any fabrication problems that might occur with the material and designs selected for the garments as well as to assess user acceptance and to identify any design modifications that user performance might dictate.

D. Field Tests

The final step in this program is extensive field testing of the developed garments. The planning required for the field tests was initiated and implementation is anticipated during CY 1975.

The purpose of these field tests is to evaluate the acceptability and effectiveness of lightweight, continuous-wear, limited-threat protective garments in operational usage.

CHAPTER III. OPERATIONAL REQUIREMENTS

The operational requirements for the protective garments developed under this program were established by the predominent threat against which protection is to be provided and the general operational environment in which such garments are to be deployed. Based on the conclusions presented in Section III.A, the common handgun (.38 special or less) was specified by the NILECJ as the weapon against which protection is to be provided. The operational environment and conditions under which the garments are to be used were established by consultation with typical law enforcement agencies and assessment of their operation and needs.

As previously mentioned, the MITRE Corporation performed preliminary operational requirements early in the program. After review by the Institute, these requirements were appropriately adjusted and became the operational requirements and target objectives for the effort under this program.

A. Threat Assessment

Since 1960, the number of fatalities and serious injuries among law enforcement personnel caused by guns has increased about 15% each year. Approximately 1000 officers and a number of public figures have been shot and killed during this period. Many of the law enforcement fatalities occurred unexpectedly and could have been prevented if appropriate body armor protection had been available and used during routine operations.

As previously mentioned, commercially available body armor is usually heavy and conspicuous, and generally not worn unless immediate danger is anticipated. Thus, a recognized need exists for inconspicuous, flexible, lightweight, and relatively inexpensive protective garments for use by law enforcement personnel and public figures.

Prior to initiating the development of any protective garment specifically intended for use by law enforcement personnel and key public figures, the identification and assessment of the specific threat characteristics against which protection is intended is obviously appropriate. Such an effort was initiated in the early phases of this program by the MITRE Corporation and involved the collection and examination of data on assaults against police as well as data on the categories of weapons confiscated by police.[3] Data sources included the International Association of Chiefs of Police (IACP), the FBI Uniform Crime Report Section, and the police departments of Detroit, Atlanta, Chicago, and New York.

A universal threat prediction is not possible, for the threat will change with time and location. Nevertheless, several independent attempts have been made to assess the threat against law enforcement personnel, and useful data have been assembled and are available on assaults, fatalities, and weapon-type distribution among confiscated weapons. An examination of national ammunition sales was also undertaken, but the results were inconclusive for several reasons, including the availability of self-loaded and foreign ammunition.

1. <u>Assault and fatality surveys</u>. The growth of police assault fatalities since 1960 is presented in Figure 3. The trend is of great concern, especially to cities with a population greater than 250,000. Their assault rate is highest, with one out of every 125 officers injured during 1972 with either a firearm or a cutting weapon.

According to the IACP,[4] there were 1787 reported police casualties between 1 July 1970 and 30 June 1971 for which the severity of the wound and the type of weapon used to inflict the wound were known. There were a total of 110 police fatalities during this period, and firearms were responsible

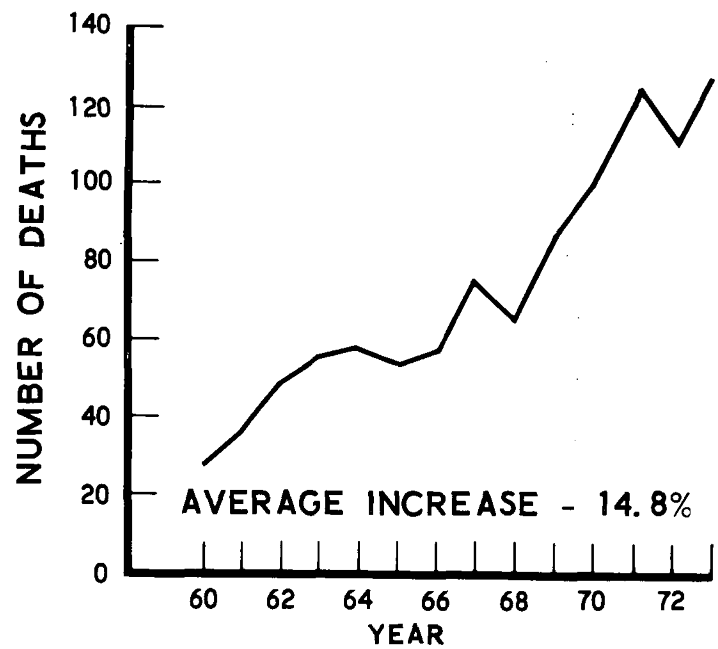


Figure 3. Historical Growth of Police Assault Fatalities

for 92% of these. Handguns caused 78% of the firearm fatilities for which the type of firearm was known. Moreover, the probability of death resulting from a handgun wound was 22%. Approximately 70% of the wounds that required hospitalization were inflicted by handguns. The torso was the most serious target area. Of the fatal wounds, 40% were in the torso area and were almost entirely caused by firearms (38%).

Statistics from the FBI Uniform Crime Reports for 1971 and 1972 indicate 229 officer fatalities due to firearms during this 2-year period. Handguns accounted for 73% of this total, and common handguns, such as the .38, .32, .25, and .22 caliber, caused over 75% of the total number of handgun fatalities.

Because a protective garment may also be effective against knife assaults, it is interesting to examine the frequency of knife attacks and the resulting fatalities. According to the IACP data,[4] knives were used in only 5% of the assaults for which a weapon was known and caused less than 4% of the fatalities. Also the probability of a fatal wound from a knife attack is only 4%. Thus, it appears that although some benefit may be derived from protection against knife assaults, the major benefit of protective garments will be against firearm, specifically handgun, assaults.

Additional data assembled by MITRE,[3] included police assault statistics with firearms, knives, or other cutting weapons during 1972 for the cities of Detroit, Chicago, and Atlanta. The combined data are summarized in Table 1. Approximately 80% of the firearm assaults were committed with handguns; of the handguns identified, 94% of the assaults were committed with common handguns (.38, .380, .32, .25, and .22 caliber).

Table 1. Combined 1972 Assault Data for Detroit, Chicago, and Atlanta

Weapon	Number of Assaults		Fraction of Total Assaults (%)	Fraction of Total Handguns (%)
Handguns	208		63	
- Common		129		62
.38, .380, .32, .25, .22 caliber				
- Higher energy		8		4
.45, .375 caliber; 9mm;				
44 magnum				
- Not identified		71		34
Rifle	22		7	
Shotgun	32		10	
Knife or other cutting weapon	67		20	
Total	329		100	100

Subsequent to the initial MITRE effort, additional data on officer fatalities from firearms were obtained by Aerospace from the FBI Uniform Crime Reporting Section for the years 1964 through 1973. These data are presented in Figures 4 through 6. As is evident from Figure 4, the general trend of officer fatalities due to firearms has increased significantly during the past decade. Although the proportion of fatalities due to handguns varied during this period, individual years did not depart significantly from the

10-year average of 74% (Figure 5). Handguns in the .22 to .38 caliber range caused the majority of the handgun fatalities. Although there appears to be a trend developing toward the use of more powerful weapons, on the average weapons in the .22 to .38 caliber range caused 81% of the handgun fatalities during the past decade (Figure 6). In general, these data tend to substantiate the original MITRE findings.

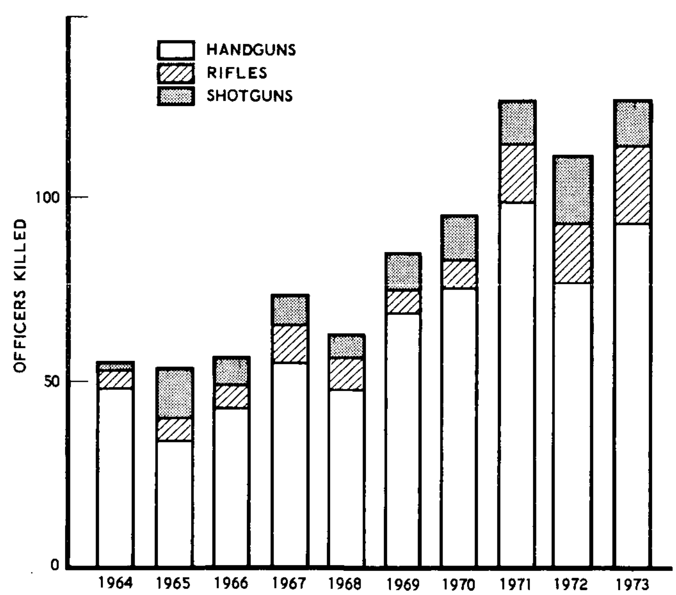


Figure 4. Annual Officer Fatalities Caused by Firearms

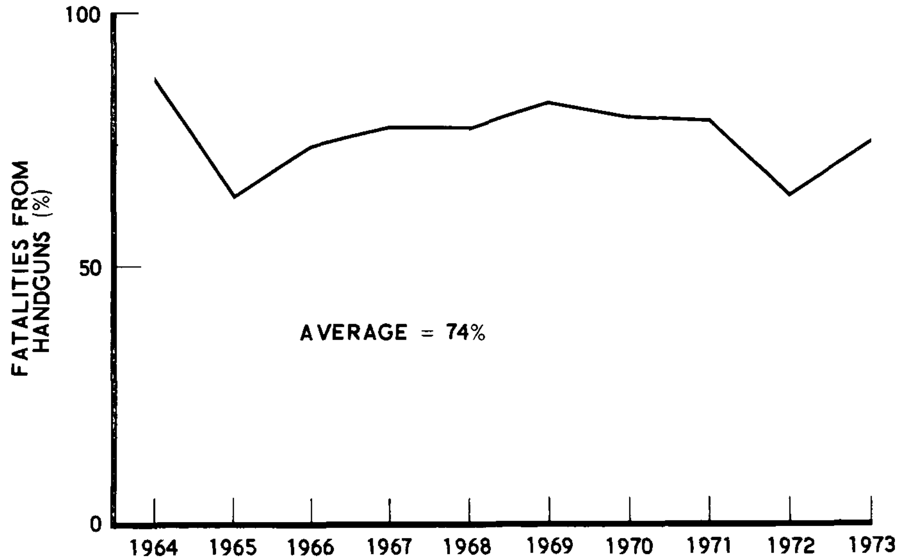


Figure 5. Officer Fatalities Caused by Handguns

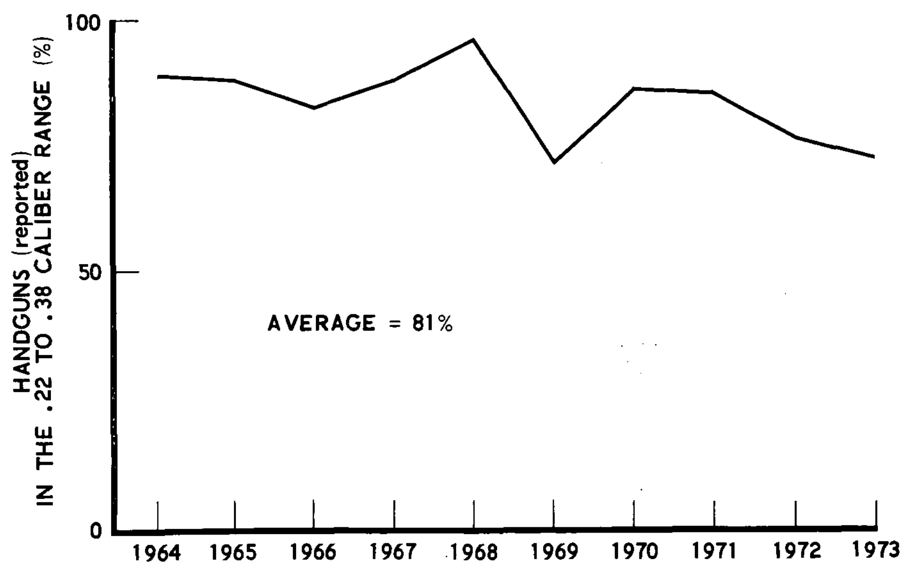


Figure 6. Portion of Officer Fatalities Due to .22 and .38 Caliber Handguns Only

2. Confiscated weapons survey. An examination of firearms confiscated by police is also a useful means of providing an indication of the assault threat posed by such weapons. As reported by MITRE, the firearms section of the New York City Police Department recorded the distribution of handgun types confiscated over a 4-month period. Out of a total of 1350 handguns seized, only 48 (or 3.6%) were in the category of high-energy handguns (.45 and .455 caliber; 9mm; .22, .357, .41, and .44 magnums). The remainder were all classified as common handguns.

A similar survey of confiscated handguns was reported by the IACP.[5] Out of a total of 13,300 confiscated firearms, 77% were in the category of common handguns (.38, .32, .25, and .22 caliber), 6% were categorized as other handguns (higher power), and 17% were in the rifle shotgun category.

An analysis was also made by Aerospace of the firearms confiscated in a typical large city during 1973. A total of 2769 firearms were confiscated, and the number of firearms in each category is indicated in Table 2. The distribution of these weapons is plotted in Figure 7. Approximately 65% were in the category of a .38 special or smaller handgun (.38, .32, .25, .22 caliber). Less than 6% were higher-powered handguns (9mm, .357 and .44 magnums). Over 16% were shotguns, and over 12% were rifles. Of the total number of handguns confiscated, 92% were in the common handgun category.

Table 2. Category Distribution of Firearms Confiscated in a Typical Large City in 1973

Common Handguns	
.22 cal	528
.25 cal	218
.32 cal	317
.380 cal	31
7.65 mm	24
6.35 mm	9
.38 cal	685
	1812
Other Handguns	
.357 mag	43
.45 cal	42
9 mm	50
.44 cal	12
.41 cal	7
	154
Shotguns	
All guages	455
Rifles	
Low Power (.22 and .30 carbine)	271
Highpower	74
Miscellaneous	3
Total	2769

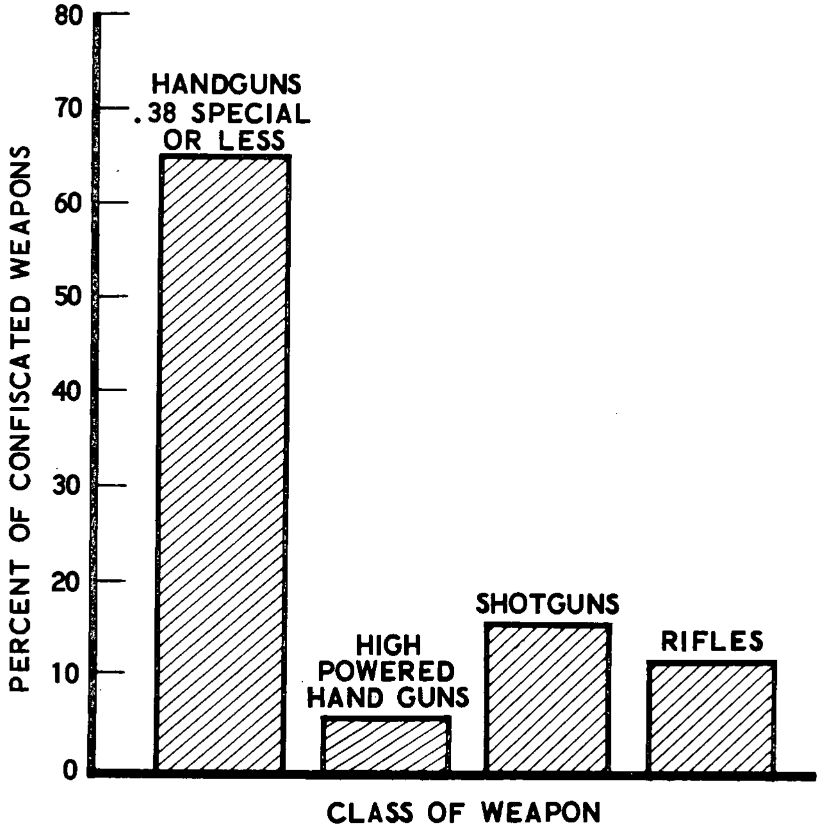


Figure 7. Distribution of Firearms Confiscated By Police in a Typical Large City (1973)

3. Ballistic energy. A meaningful appreciation of the variation in the firearm threat is provided by examining the bullet muzzle energy and velocity. These parameters have been plotted in Figure 8 for a variety of firearms. Also included in Figure 8 is a tabulation in ascending values of muzzle energy for general weapon type according to the standard groupings of the National Bureau of Standards. This tabulation and the plotted data have been divided into three groupings, according to the level of muzzle energy. The common

handgun (.38 special or less), which has been shown in Sections III.A.1 and III.A.2 to present the greatest assault threat, fortunately falls in the grouping with the lowest muzzle energy. Moreover, the characteristics of the handguns in this grouping also include generally low muzzle velocities.

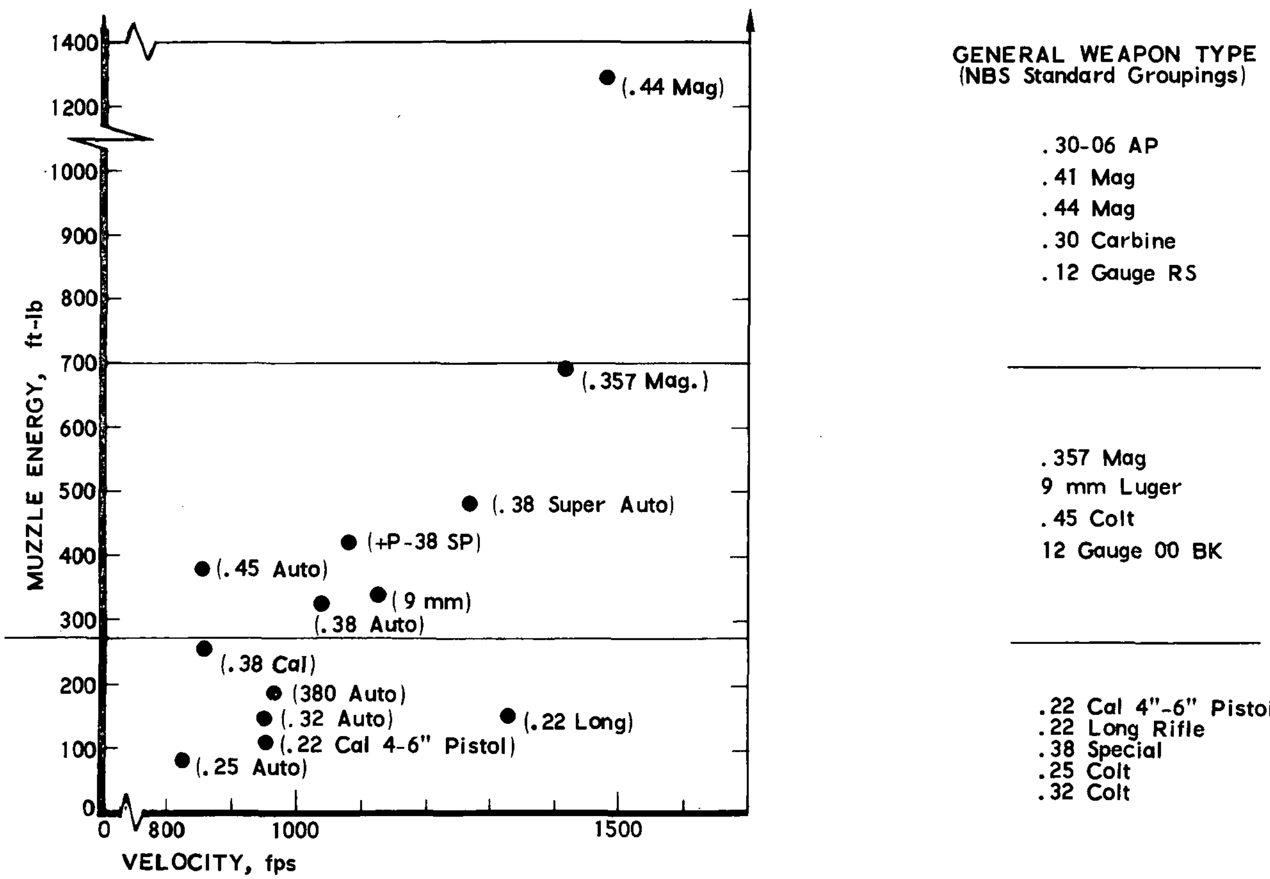


Figure 8. Muzzle Energy/Velocity Characteristics of Common Firearms

4. Summary. Because current technology does not permit development of lightweight, inconspicuous, continuous-wear garments for protection against all threats, a reasonable level of threat protection must be defined. It was recognized that an absolute determination of the threat is unlikely. Several independent approaches were therefore utilized to establish the type of weapons both available and used against law enforcement personnel, and the degree of threat posed by such weapons.

It was rapidly concluded that firearms pose the greatest threat against which protective garments can be effective. Although not all firearm assaults are in the torso area (the area generally covered by a protective garment), most fatal torso wounds are caused by firearms. A summary of several individual surveys on firearms either confiscated by police or used in assaults on police is presented in Figure 9. If, as is believed, the actual threat falls within the distribution indicated, then it must be concluded that among firearms the common (.38 special and smaller) handgun poses the greatest assault and fatality threats.

B. MITRE Inputs

The operational requirements prepared by the MITRE Corporation were organized into several categories, including general requirements, weapon threat requirements, physical mobility, and comfort and appearance. Protection against several weapons, including the .38 caliber handgun, was suggested. The acceptable level of wearer incapacitation and the body area to be protected were also specified. Physical mobility and wearer comfort

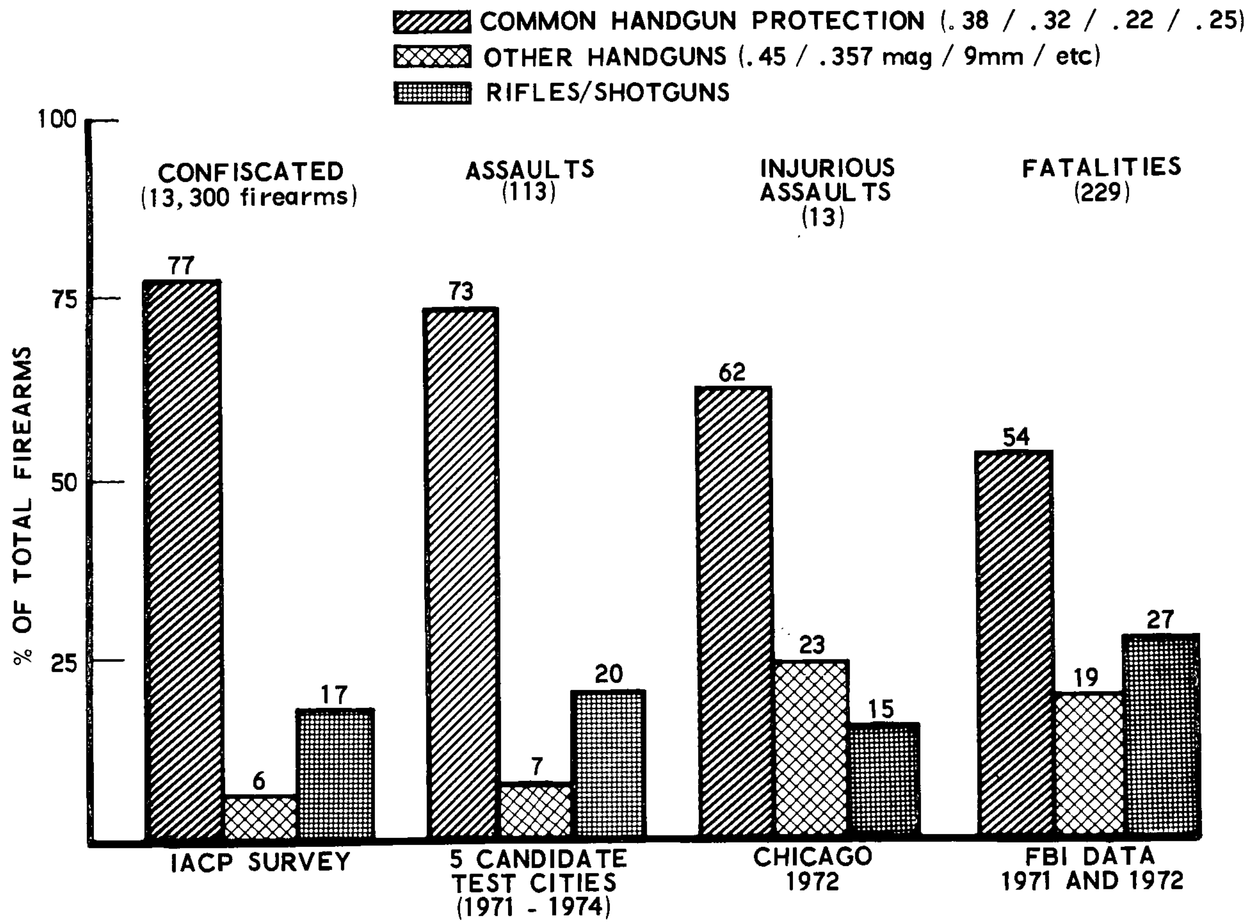


Figure 9. Summary of Firearm Threat Data

were expressed in terms of the environments in which wearers are expected to operate. Specific MITRE recommendations are summarized in the sections that follow.

1. <u>General requirements</u>. The protective garments to be developed should be compatible with an officer's regular clothing and simultaneously

provide protection from incapacitation or death due to firearm assaults. Functional application of these garments should address use by:

- Mobile patrolmen
- Foot patrolmen
- Detectives
- Undercover agents
- Prison guards
- Courtroom bailiffs
- Key public officials

Each garment should carry a label stating the:

- Limits of protection provided
- Manufacturer
- Size
- Identifying serial number

2. Protection to be provided. The protective garment should prevent bullet penetration through the inside layer of protective material.

The wearer of the garment should not suffer irreparable body damage as a result of the blunt trauma induced by ballistic impact on the protected area. Irreparable body damage is defined as impairment of a body function or a body organ that cannot be medically or surgically repaired.

The wearer should not lose consciousness following a ballistic impact in a protected area and should be able to defend himself and call for assistance.

The garment should provide protection to the upper torso area of the wearer.

3. Required physical mobility. The garment should not impede the performance of the wearer's normal duties.

4. Comfort and appearance. The garment is intended for full-time wear during normal duty and must be comfortable and convenient to wear in order to encourage its full-time use.

The garment should be unobtrusive and inconspicious and must provide a neat appearance.

5. Maintainance and serviceability. Consideration must be given to the various environmental conditions to which uniform-type clothing are exposed. These include aging, moisture, heat and cold, and body temperature and perspiration.

Garments should be capable of being either laundered or dry cleaned with no degradation of ballistic protection nor appreciable shrinkage.

C. Requirements Summary

The suggestions submitted by MITRE were reviewed by project personnel at NILECJ. Based upon this review and the statistics previously assembled and discussed in Section III. A, the following operational requirements were established as goals for the development phase of this program:

- The garment should be inconspicuous to the casual observer.
- The garment should not hinder the wearer's performance of his assigned duties nor access to his weapon.

- The garment protection should not be degraded by use and exposure to the operational environment.
- The garment should prevent penetration of a .22 caliber, 40-grain ballistic projectile at 1000 feet per second. It should also protect against penetration with acceptable blunt trauma of a .38 caliber, 158 grain projectile at 800 feet per second.
- The blunt trauma response should not prevent the wearer from immediately defending himself nor should it result in any permanent injury.

CHAPTER IV. GARMENT DEVELOPMENT

When protective armor is worn, the dissipation of the kinetic energy of a bullet is divided among three separate phenomena: bullet deformation, interaction with and deformation of the protective armor, and interaction with and deformation of the body of the wearer. To properly design lightweight body armor, it is important to understand these phenomena, particularly how they are influenced by various garment design parameters.

With soft body armor, stopping the bullet motion is accompanied by a relatively large deformation of the protecting material. This deformation is transmitted to the body which, in turn, also absorbs energy by deformation. If skin tolerance is exceeded, a contusion on the skin surface will result; if the deformation is sufficiently rapid and deep, damage to internal organs may occur. This damage to the body behind protective armor is termed "blunt trauma," and the amount of blunt trauma the body can absorb determines how flexible and lightweight the armor can be made.

The factors that must be considered when undertaking the development of protective body armor were identified in Figure 2. The major effort under the development testing phase of this program addressed the interaction of these factors in mitigating the kinetic energy and momentum of the bullet and preventing penetration through the protective garment or subsequent serious blunt trauma medical injury. Both analytic and experimental activities were involved and covered material assessment and evaluation, the mechanics of ballistic protection, ballistic testing of the candidate material, environmental testing of the candidate material, and a preliminary assessment of blunt trauma.

A. Material Assessment and Selection

The objective of the initial FY 73 effort was to evaluate a variety of candidate fabric materials for use in protective garments. The U. S. Army Natick Laboratories in Massachusetts provided guidance and data in the preliminary selection of material candidates. Additional information on materials was acquired from a survey of manufacturers of material and protective armor. Based upon these inputs, the following material selection criteria were established:

- Weight-to-strength ratio. Lightweight but sufficiently strong to prevent bullet penetration and minimize blunt trauma.
- Fabric flexibility. Allows wearer freedom of movement.
- Inexpensive. Acceptable for extensive procurement for law enforcement applications.
- Tailoring feasibility. Capable of being tailored into garments with inconspicuous fit and styling.

Forty specimens of 12 types of fabric (including nylon, rayon, boron, graphite, and Kevlar) and covering a range of yarn and weaving types were ballistically tested at the U. S. Army Edgewood Arsenal in Maryland. A summary qualitative assessment of the candidate materials is given in Table 3. Kevlar-29, a DuPont synthetic fiber originally developed for use as a tire cord material, was ultimately selected as being most promising for protective garment application.

Table 3. Protective Material Evaluations

MATERIAL	MANUFACTURER	SELECTION CRITERIA: WEIGHT TO STRENGTH PENETRATION CHARACTERISTICS	FLEXIBILITY (non rigid)	COST	BLUNT TRAUMA	TAILORING
NYLON	DUPONT	P	G	G	G	G
RAYON	DUPONT	P	G	G	P	G
DACRON	DUPONT	P	G	G	P	G
KEVLAR 29	**DUPONT**	**G**	**G**	**F**	**G**	**G**
KEVLAR 49	DUPONT	F	G	G	F	G
THORNEL GRAPHITE YARN	UNION CARBIDE	P	P	P	P	P
PANEX GRAPHITE YARN	UNION CARBIDE STACKPOLE INC	P	P	P	P	P
MARLEX X-P	PHILLIP 66	G	P	P	G	P
X-55 FIBER	MONSANTO	P	F	F	P	F
NYLON FELT	DUPONT	P	P	P	P	P
X-500 FELT	MONSANTO	P	P	P	P	P

G = GOOD F = FAIR P = POOR

The properties of Kevlar-29 yarn that influence its utility as a soft body armor material are given in Table 4. This yarn combines a very high strength and low elasticity (3 to 4% strain to failure) with light weight and excellent toughness. It has good environmental stability and flame resistance, and maintains its properties over a wide range of ambient temperature. Moreover, it is already available as a continuous filament yarn in a range of deniers (200, 400, 1000, and 1500) and types for numerous other industrial

Table 4. Physical Properties of Kevlar-29 Yarn

Parameter	Property	Comment
Density	1.45 g/cc	Forty percent less than glass or boron
Tensile Strength	400,000 psi	Substantially above conventional organic fibers, greater than steel
Modulus	19×10^6 psi	Twice that of glass fibers
Chemical Resistance	Good	Resistant to solvents, fuels and lubricants; can not be dyed
Temperature Resistance and Flammability	Excellent	No degradation in short-term exposures to 500°F, self-extinguishing
Textile Processibility	Excellent	Readily woven on conventional looms

applications such as cables, ropes, webbing, tapes, and fabrics. Finally, as a yarn, Kevlar-29 can be woven into specified fabric designs, an advantage when undertaking new protective garment development. Current Kevlar production capability is 6 million pounds per year, and a plant that will produce 50 million pounds per year is presently under construction. Material shortage should not be a problem.

The ballistic tests leading to the selection of Kevlar-29 were conducted primarily with a .38 caliber, 158 grain lead bullet at a muzzle velocity of approximately 800 feet per second. Complementary tests were also made with a 4-inch barrel, .22 caliber weapon with a bullet velocity of 1000 feet per second. During these tests, it was observed that after impact the bullets varied in shape and deformation depending upon the type of protective material being tested and the number of plies used. For example, when impacted against the ballistic nylon materials, partial bullet penetration often occurred and there was no evidence of increased bullet deformation as the areal density of the nylon material was increased. On the other hand, the bullet did not penetrate even 5 plies of Kevlar-29, and increased bullet deformation occurred as the number of Kevlar-29 plies was increased. Photographs of bullets (Figure 10) following ballistic tests of nylon and Kevlar-29 samples illustrate the observed bullet deformation differences as a function of areal density (weight per unit area of protective material). Such tests provided the first indication of the improved capability offered by Kevlar and suggested that a better understanding of the physical interaction mechanisms might lead to further improvements.

1. Preliminary ballistic testing of Kevlar-29 material. Ballistic testing of Kevlar-29 fabric samples was conducted by the U.S. Army Edgewood Arsenal, with complementary testing performed by The Aerospace Corporation using the facilities of Sierra Engineering Company in Sierra Madre, California, and the Atomic Energy Commission's Lawrence Livermore Laboratory in Livermore, California. The purpose of these tests was to

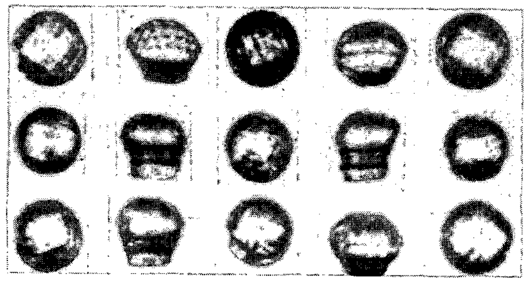
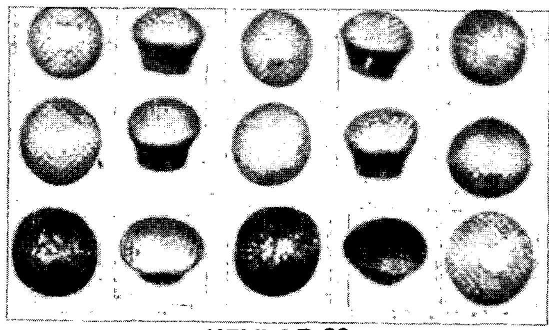
AREAL DENSITY	No. OF PLIES	BULLET SAMPLES	REMARKS
1.1 lb/ft^2	12		• PARTIAL PENETRATION ON SOME SHOTS • NO TREND EVIDENT FOR BROADER ENERGY SPREADING WITH GREATER BACKING
1.7 lb/ft^2	18		
2.2 lb/ft^2	24	BALLISTIC NYLON	
0.2 lb/ft^2	5		• ALL PROJECTILES, NO PENETRATION • TREND FOR BROADER ENERGY SPREADING WITH GREATER BACKING
0.7 lb/ft^2	16		
1.1 lb/ft^2	23	KEVLAR-29  	

Figure 10. Examples of Effect of Material Characteristics on Bullet Flattening

provide the experimental inputs needed to guide the design of the protective garments in order to prevent bullet penetration and to minimize blunt trauma.

In-house Aerospace tests were primarily devoted to rapidly screening a range of deniers, weaves, plies, thread twist, and fabric composites to support definition of Kevlar fabric weaving specifications. These preliminary tests were complemented by more comprehensive ballistic testing at Edgewood Arsenal to identify the baseline ballistic protection provided by each sample. The criteria of merit were whether or not the bullet penetrated the test sample, the degree of bullet deformation, and the size of the cavity in the backing material.

Various backing materials were used, including animal, clay, and gelatin backings, and each provided specific information. Animal backing provided medical information, clay backing provided a permanent measure of the energy absorbed by the backing, and gelatin backing permitted obtaining high-speed photographs of the time-dependent deformation of the protective material and the backing.

Ballistic tests on the backface signature trends were also performed by the Lawrence Livermore Laboratory. These tests and those at Edgewood Arsenal covered a range of independent parameters such as bullet energy, fabric denier and plies, and armor standoff distance from the backing. In addition to whether or not penetration occurred, the tests also included assessment of the volume of deformation, depth of bullet penetration, and the time growth of the deformation.

2. Preliminary Kevlar fabric screening. The various Kevlar-29 deniers and weaves that were screened for ballistic resistance are summarized in Table 5. These tests were performed at the Sierra Engineering Company facility and utilized an unconstrained clay or a rubber backing.

Table 5. Specimens of Kevlar-29 Fabric Screened for Ballistic Resistance

Denier/Weave (thread count)	Per Ply Areal Density (oz/sq yd)	Ballistic Test	General Penetration Results[a]
200 (60 X 58)	3.2	.38 cal (158 gr.) .22 cal (40 gr.)	N.P. - 7 plies N.P. - 7
200 (110 X 90)	4.8	.38 cal .22 cal	N.P. - 5 C.P. - 5
1500 (24 X 23) Style 71	13.5	.38 cal .22 cal	N.P. - 5 C.P. - 6
400-1 (65 X 40) plain weave	6.0	.38 cal .22 cal	N.P. - 7 C.P. - 5
400-1 (65 X 65) basket weave	6.5	.38 cal .22 cal	N.P. - 7 C.P. - 6
1000 - (31 X 31)	8.5	.38 cal .22 cal	N.P. - 7 C.P. - 5
400-2 (32 X 32)	7.3	.38 cal .22 cal	N.P. - 7 C.P. - 5
400-2 (36 X 36) plain weave	8.0	.38 cal (158 gr.) .22 cal (40 gr.) 9 mm (124 gr.) 357 mag (159 gr.) .38 cal super velocity (115 gr.) .32 cal (71 gr.) 380 cal (95 gr.)	N.P. - 7 C.P. - 5 C.P. - 15 C.P. - 10 N.P. - 7 N.P. - 7 N.P. - 7
<u>Composites of Kevlar</u>			
5 plies 400-2 and 3 plies 200		.22 cal	N.P. at velocity of 1050 fps
4 plies 200 and 4 plies 400-2		.22 cal	N.P. at velocity of 1000 fps
3 plies 200 and 4 plies 400-2		.22 cal	N.P. at velocity of 990 fps
2 plies 200 and 5 plies 400-2		.22 cal	N.P. at velocity of 1020 fps
2 plies 200 and 4 plies 400-2		.22 cal	C.P. at velocity of 1000 fps

[a] N.P. - No Penetration C.P. - Complete Penetration

It was concluded that a fabric made of 400 denier, double-twisted yarn in a 36 × 36 pics (yarns) per inch plain weave had acceptable protection properties, and that it would be acceptable for the baseline garment material and also for use in the baseline laboratory examination of the interaction process. Although the ballistic resistance of certain other deniers and ply combinations appeared superior, they involved greater cost and fabrication difficulties. Tests conducted near the end of the program suggested that a 1000 denier, single-filament yarn fabric in a 31 × 31 pics per inch plain weave provides protection at least equivalent to the baseline material and at a lower cost.

The result of a typical successful ballistic test of Kevlar is illustrated in Figure 11. Although a minor depression is created in the fabric, bullet penetration is resisted and no fibers are broken. Deformation of the bullet with the weave pattern impressed on the blunted foresection is clearly apparent. For a given bullet type, the degree of bullet deformation depends upon the material denier, the tightness of the weave, the number of plies, and the backing material.

Comparative photographic results are shown in Figure 12 for 400 and 200 denier Kevlar fabric specimens impacted by .38 and .22 caliber bullets. A comparison between Figures 12 (a) and 12 (b) reveals that when a .38 caliber bullet impacts the lighter (200 denier) and tighter woven fabric, the bullet is flattened to a greater degree and its force is distributed over a larger area. When a .22 caliber bullet impacts the 400 denier fabric, it penetrates by separating the yarn fibers (without breaking them) and is only

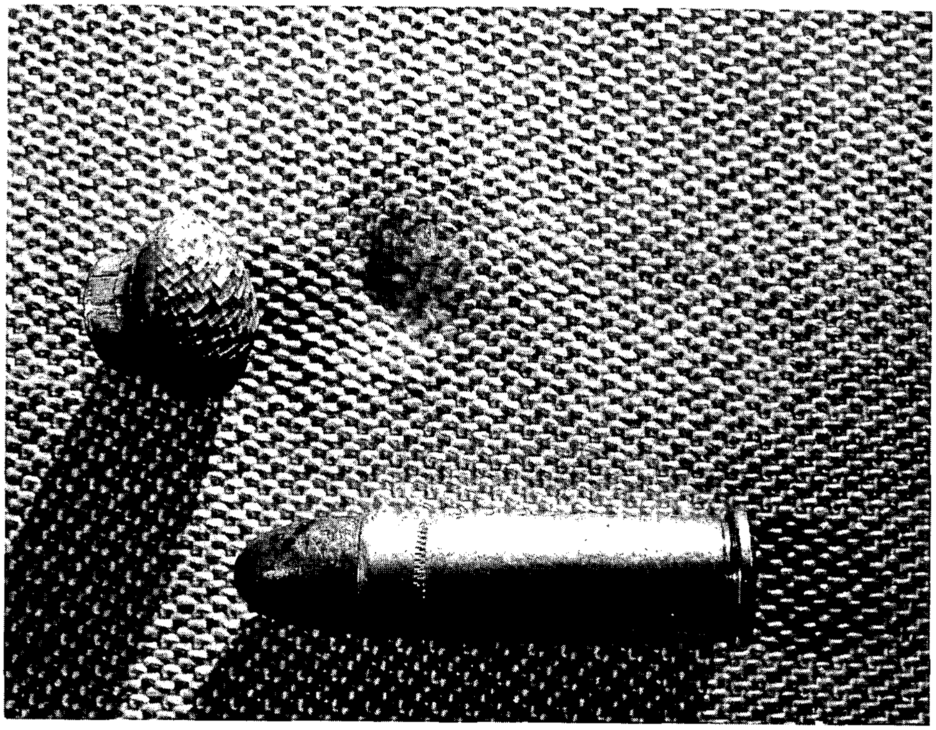


Figure 11. Specimen Material Ballistic Test

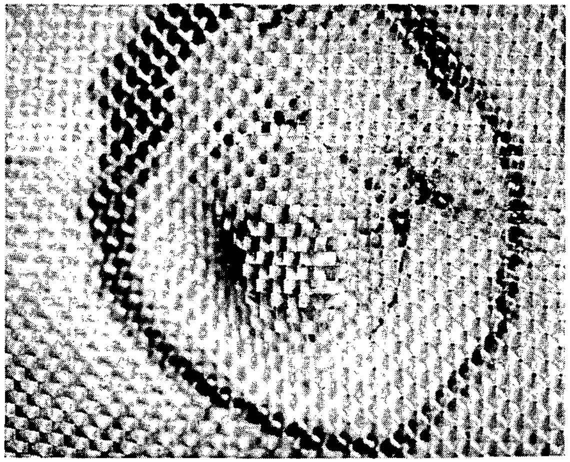
partially deformed, Figure 12(c). On the other hand, with the lighter, tighter woven fabric, Figure 12(d), a .22 caliber bullet does not penetrate and is deformed in a manner similar to the .38 caliber bullet. These results illustrate the advantages of the tighter weaves for any denier yarn.

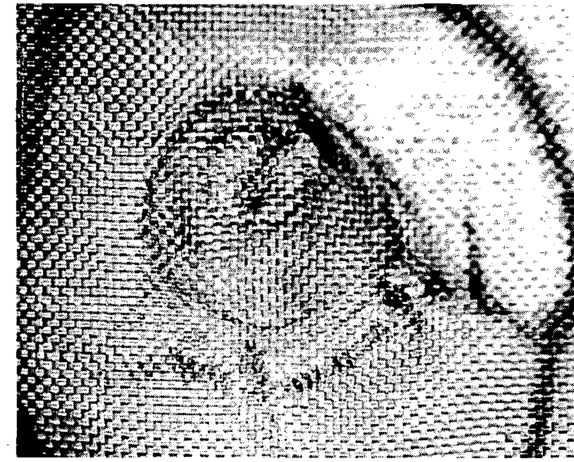
3. Kevlar fabric specifications. As discussed in Sections IV. A and IV. A. 1, a number of Kevlar fabrics were evaluated in the early stages of the program, and one specimen (a 400-2, 36 × 36 fabric) was selected as the baseline material for subsequent development effort.

To provide appropriate control over the quality of the baseline fabric and consistency in its characteristics, The Aerospace Corporation, aided by DuPont, generated a 400-2 Kevlar weaving specification (Appendix B,

400 DENIER FABRIC

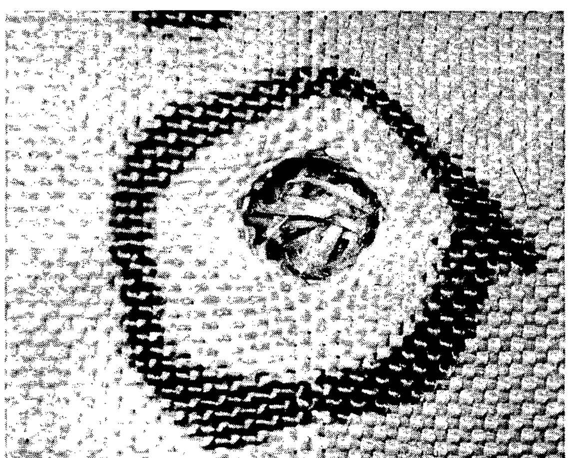
200 DENIER FABRIC

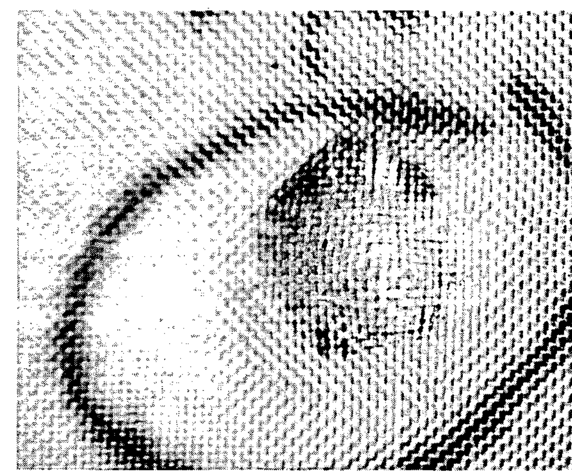




(a) IMPACTED BY .38 CALIBER
158 GRAIN, ~800 fps

(b) IMPACTED BY .38 CALIBER
158 GRAIN, ~800 fps





(c) IMPACTED BY .22 CALIBER
40 GRAIN, ~1000 fps

(d) IMPACTED BY .22 CALIBER
40 GRAIN, ~1000 fps

Figure 12. Kevlar Ballistic Impact Comparison for 400 and 200 Denier Specimens

Volume III). The specification identifies material requirements, quality assurance provisions, and woven fabric characteristics. Some of the items covered in the specification are also included in the characteristics listed in Table 6.

Based on the 400 denier weaving specification, DuPont later wove a 1000 denier, 31 × 31 fabric in a similar, tightly woven configuration that appears to yield equal or possibly even better ballistic resistance and at lower cost. Insufficient documentation and medical testing was available to justify its substitution as the baseline material. However, in the long term, this 1000 denier fabric may have a greater potential than the 400 denier fabric.

Table 6. Kevlar Material Characteristics

Style	100
Yarn	400 denier, 267 filaments, 2 ply, three twists per inch, "Z" twist
Yarn count	36 warp, 36 fill per inch
Weave	1 × 1 plain weave
Finish	Cloth shall be scoured and Zepel coated
Weight	8 oz/yd^2
Cost	Under $18.00 per yard woven (approximately $14.50 per pound yarn)

In addition to fabric cost and weave characteristics, quality assurance testing requirements to be demonstrated by the weaving contractor were also specified (Table 7). An air permeability specification was included to establish the tightness of the woven fabric.

If loose or missing yarns are not detected during the in-process inspection, an air permeability test will reveal the defect by allowing a greater air flow through the fabric. Measurement of the air flow rate through material is normally made with a Gurley 4307 instrument and verifies the consistency of weaving. As a matter of interest, air permeability values for typical Kevlar weaves are given in Table 8. Also included is a value for ballistic nylon.

Ballistic resistance test requirements are also included in the fabric specifications. Tests are conducted on a 12 × 12 inch specimen of the material with Plastellina-Grade 1 clay as a backing. Six impacts are required from a firing distance of ten feet without complete penetration. The projectiles used are a .38 caliber, 158 grain bullet at 800 feet per second muzzle velocity and a .22 caliber, 40 grain bullet at 1000 feet per second.

B. Laboratory Testing of Kevlar Armor

The laboratory testing performed during the initial phases of the program addressed feasibility assessment and identification of a candidate material and a baseline fabric design for use in lightweight, inconspicuous, protective garments (Section IV. A). Subsequent laboratory testing and analysis, performed during FY 1974, were aimed at improving understanding of the interaction between the bullet, the protecting material, and the

Table 7. Woven Kevlar Quality Assurance Specifications

Test	Applicable Specifications
Weight	ASTM 1910 Construction Characteristic of woven fabric
Nominal thickness	ASTM D579 Breaking loads and elongation of textile fabrics
Fabric count	ASTM 1910
Breaking strength	ASTM D1682 Breaking load and elongation of textile fabric
Permeability	ASTM 737, Air permeability of textile fabric
Ballistics	MIL-Std. 662 - Ballistic Acceptance Test Method for Personal Armor Material and NILECJ-Std. 0101 Ballistic Resistance and Police Body Armor

Table 8. Typical Air Permeability Values

Material	Air Permeability (cu. ft. /min.)
400/2, 36 × 36	28
400/2, 36 × 36 (Scotch Guard)	46
400/2, 32 × 32	70
1000/1, 31 × 31	Less than 5
400/1, 65 × 65	Less than 5
400/1, 65 × 40	Less than 5
200/1, 62 × 58	10
Ballistic nylon 23 × 20	8

backing behind the protective fabric when bullet penetration is prevented by soft armor. Such insight is needed to minimize blunt trauma loading on the wearer of the garment.

Several complementary and coordinated test programs were undertaken during FY 74 at The Aerospace Corporation's Material Science Laboratory, the Edgewood Arsenal Biophysics Laboratory, and the Lawrence Livermore Laboratory. Somewhat different approaches and test methods were used by each, but all had the same objective, namely insight into soft body armor protection and design. A detailed discussion of The Aerospace Corporation results is included in Volume III of this report as Appendix A. The results of the Edgewood Arsenal work are being separately published.[6] The results of the Lawrence Livermore Laboratory work[7] are included as Appendix D in Volume III of this report.

A discussion of the various approaches and test methods utilized at these three laboratories and highlights of the results obtained are presented in the subsections that follow.

1. <u>Ballistic testing</u>. Complementary baseline ballistic tests were independently performed by the Edgewood Arsenal Biophysics Laboratory and the Lawrence Livermore Laboratory to obtain backface signature data behind protective Kevlar fabric. The term "backface signature" includes such characteristics as volume of deformation, depth of penetration, and time growth of deformation and aids in assessing the anticipated blunt trauma loading. The basic test matrix was developed by The Aerospace Corporation and covered a range of independent parameters such as bullet velocity, bullet

diameter, bullet weight, material plies, and the standoff distance of the test sample from the gelatin backing. A summary of the specified test conditions is given in Table 9. Because the tests were intended to indicate trends and to identify those parameters that should receive further examination, some departure from this basic test matrix was made by both laboratories in order to augment the results obtained in certain of the tests.

A detailed discussion of the specific tests made, the equipment used, the data reduction procedures employed, and the results obtained is given in the final report prepared by each laboratory. As previously indicated, the Edgewood Arsenal report is being published separately, whereas the Lawrence Livermore Report is included as Appendix D in Volume III of this report.

Both Laboratories employed generally similar techniques of high-speed photography to study the backface signature. A transparent gelatin block behind the test sample offered resistance somewhat comparable to that provided by the human body and also allowed photographing the gelatin deformation as a function of time. The Lawrence Laboratory system had a 50, 000 frames per second capability. However, since the capability of the Edgewood Arsenal system was only 4000 frames per second, it was augmented by an electronic timing system, which also recorded on the film. Various deformation characteristics were then "read" from the film and processed by computer to give:

- Penetration depth
- Velocity of deformation

Table 9. Matrix of Ballistic Tests Performance With Kevlar-29, 400/2 Denier Fabric

Test No.	Bullet Size	Bullet Weight (gr)	Muzzle Velocity (ft/sec)	No. of Plies	Armor Standoff Distance (in.)	Remarks
1	.38 cal	158	800	3 5 7 9 15	0	Effect of number of plies on backface signature
2	.38 cal	158	800	7 7 15	0.5	Effect of plies and standoff distance on backface signature
3	.38 cal	158	600 700 900 1000	7	0	Effect of muzzle velocity
4	.22 cal	40	1000	7 15	0	Effect of smaller caliber bullet and higher muzzle velocity
5	9mm	115 (jacketed)	1150	15 23	0	Effect of number of plies with bullet of increased energy
6	.22 cal .32 cal .38 cal	40 101 158	1600 1000 800	7	0	Constant kinetic energy of 225 ft-lb with varying bullet diameter, mass, and velocity
7	.38 cal	158 101 70	800 1000 1200	7	0	Variable momentum at constant kinetic energy of 225 ft-lb

- Deformation surface area
- Deformation volume (and radius of depression)

a. Test results. Typical results obtained during the backface signature ballistic tests are indicated in Figures 13 through 16. High-speed photographs, (Figure 13) show the development of the backface cavity in gelatin backing as penetration is prevented by the armor test sample. The development of the height and base diameter of the depression created as a

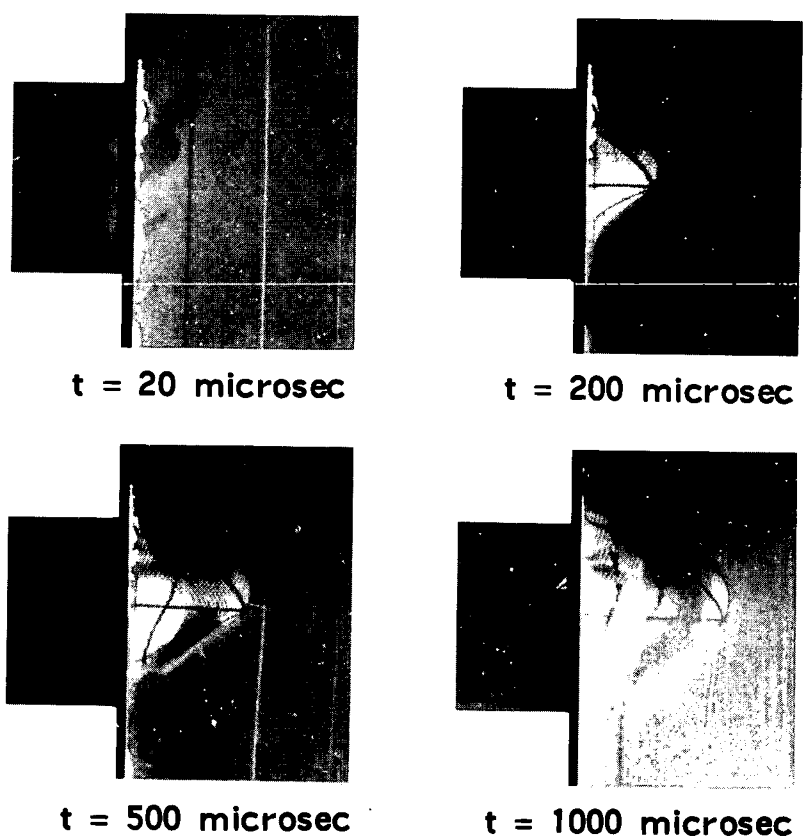


Figure 13. High-Speed Photographs of Backface Cavity Development (.38 caliber bullet, Kevlar material, gelatin backing)

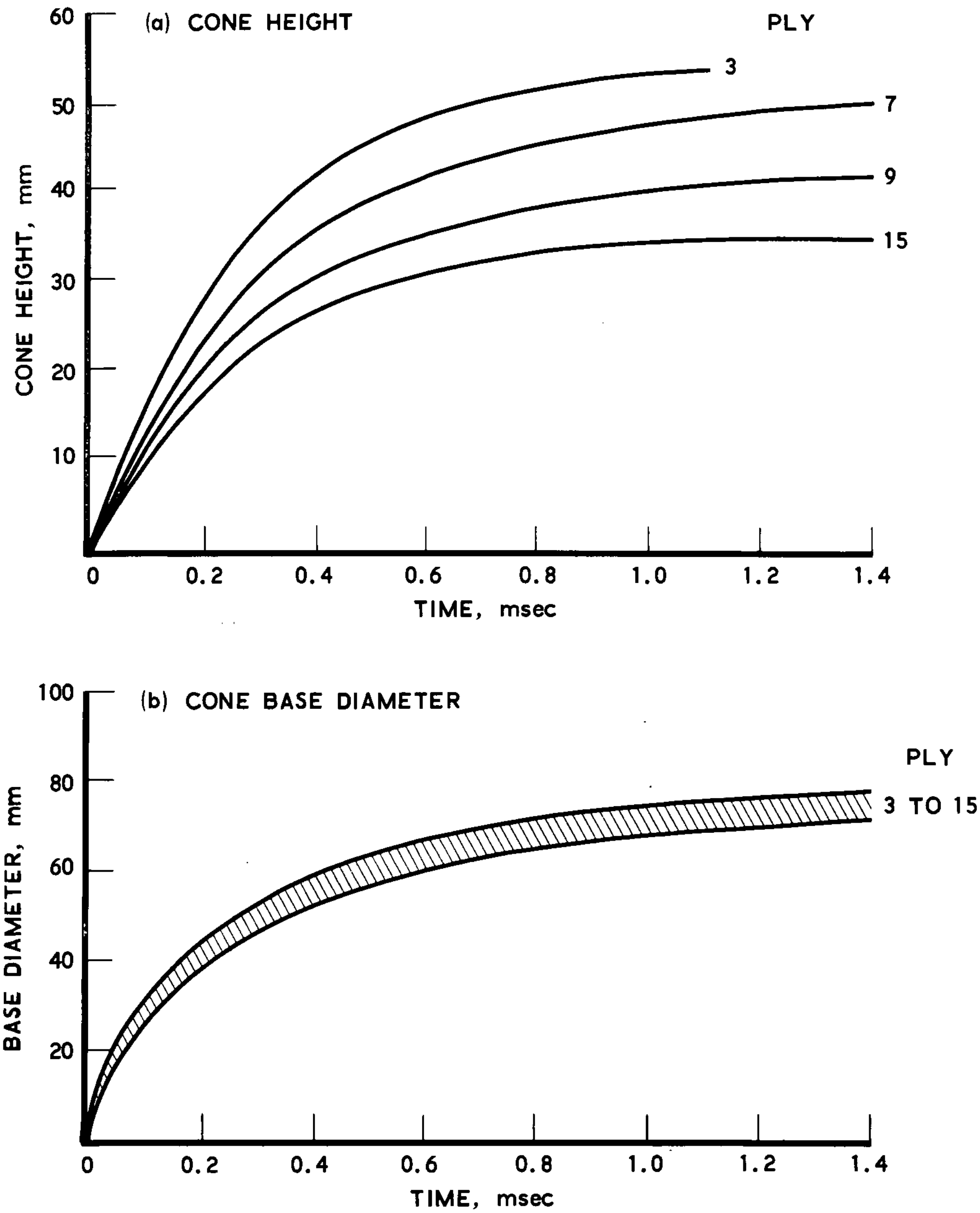


Figure 14. Formation of Impact Depression as a Function of Time and Plies (Kevlar-29, 400/2 denier; .38 caliber 158 grain bullet at 800 feet per second)

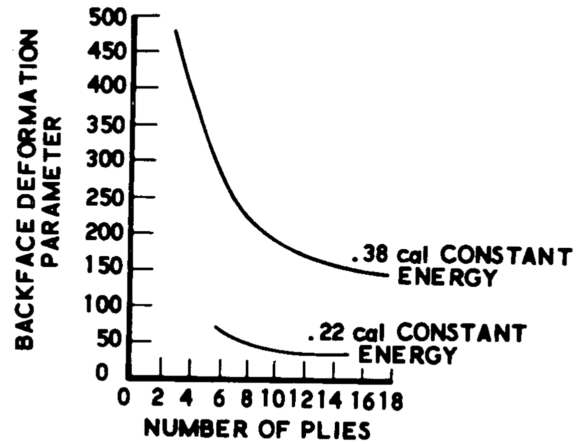


Figure 15. Typical Effect of Number of Plies on Backface Deformation

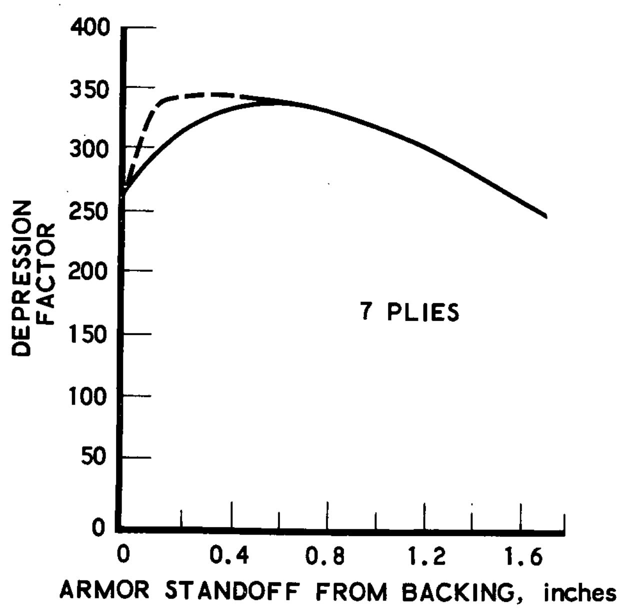


Figure 16. Typical Effect of Armor Standoff Distance on Backface Deformation

function of time is presented in Figure 14 for the Test 1 series (see Table 9). Similar data were also obtained for the other test series. As expected, increasing the number of plies caused a reduction in the maximum cone height observed. However, a negligible effect on base diameter resulted. Approximately 90% of both the maximum cone height and base diameter occurred within 0.5 milliseconds after impact over the entire ply spectrum. For nonpenetrating cases, increasing the projectile striking velocity generally increased the size of the depression.

A backface deformation parameter is used as a relative measure of the intensity of the backface signature. The effect of the number of plies used in the protective garment on this parameter is illustrated in Figure 15. The deformation with a .22 caliber bullet is considerably less than that with a .38 caliber bullet, due primarily to the lower energy in the .22 bullet. Nevertheless, both show similar trends with an increase in the number of plies. For a given bullet energy, increasing the number of plies of protective material beyond 6 to 10 is increasingly less effective in decreasing the backface deformation.

The effect of armor standoff distance from the gelatin backing is especially interesting (Figure 16). Although the shape of the curve relating the depression factor to the standoff distance is uncertain for standoff values between 0 and 0.5 inch, it would appear that either tight fitting or very loose fitting protective garments are to be preferred. Additional testing at standoff distance less than one-half inch is obviously required.

b. Backface signature correlation with other backings. One of the objectives of the backface signature tests with gelatin backing was to correlate the observed results for candidate garment materials with the backface signature obtained with a clay backing. The latter provides a permanent record of the backface signature without the need for high-speed photography. It was also intended to explore correlation with the blunt trauma observed on animals caused by torso impacts behind soft armor. A discussion of the attempt to provide such a correlation and to develop a nonbiological blunt trauma model is given in Reference 6. In general, the available data were too meager to lead to any significant method for directly relating biological and nonbiological ballistic tests of soft body armor materials.

c. Ballistic results summary. Although a biological test correlation was not established, this type of nonbiological testing did provide experimental inputs needed to guide the subsequent design of protective garments (see Chapter V). Information was obtained on the number of plies required to prevent bullet penetration of the protective garment with acceptable blunt trauma. For example, it appears that an increase beyond 6 to 10 layers (the level at which there was neither .22 nor .38 caliber penetration) offers less blunt trauma protection per ply for those energy levels. It also appears that maximum blunt trauma might occur when a gap of approximately one-half inch exists between the protective armor and the body of the wearer. As expected, increasing the striking velocity of the .38 caliber projectile or the threat severity (a 9 mm bullet for example) increased the backface signature even when the protective fabric prevented bullet penetration.

For a constant projectile kinetic energy of 225 foot-pounds, variation in mass, velocity, and even bullet diameter caused little if any change in the backface signature.

Similarly, with a projectile diameter of .38 caliber and a constant kinetic energy of 225 foot-pounds, variations in missile mass and striking velocity, i.e., momentum, also appear to have little effect on the backface signature.

Although the test sample was limited, it appears that the backface signature behind protective armor is dependent upon the striking kinetic energy, some bullet characteristics, the fabric denier, the number of plies, and possibly standoff distance.

2. Mechanics of ballistic protection. A variety of additional analytic and experimental laboratory activities were undertaken to complement the ballistic protection tests discussed in Section IV. B. 1. The primary purpose of these activities was to improve the understanding of the physical interaction between bullet, soft armor, and backing material during a ballistic encounter and lead to fabric and garment design improvements. Three basic types of tests were used:

- Static tensile tests - to determine the uniaxial material (Kevlar cloth) structural characteristics in the warp, fill, and bias directions.
- Static indentation tests - to measure the biaxial response of the fabric to a bullet-shaped indentor and steady-state loading forces.

- Dynamic indentation tests - to study the effect of dynamic loading on the interaction and deformation of the material and backing under controlled conditions.

a. Bullet energy and momentum. Results of the ballistic tests described in Section IV. B. 1 indicated that three plies of plain woven 400 denier Kevlar-29 yarn would prevent penetration of a 158 grain, .38 caliber special, round-nose bullet travelling at 800 feet per second. Seven plies of the same fabric were required to prevent penetration of a 40 grain, .22 caliber bullet at 1000 feet per second. The kinetic energy per cross sectional area of the .22 caliber bullet is approximately 5% greater than for the .38 caliber case, and obviously the basic bullet total energy represents an incomplete assessment of threat and protective capability of a given Kevlar weave.

Bullets possess both kinetic energy ($1/2\ mv^2$) and momentum energy (mv), both based on the weight of the bullet (m) and its velocity (v). Typically, a 158 grain bullet at 800 feet per second possess 225 foot-pounds of kinetic energy (about twice the energy of a professionally pitched fast ball) and 0.55 pounds per second of momentum energy. The rotational energy attributed to the bullet due to its spin is negligible relative to its linear energy.

Upon impact, the bullet momentum is transferred to the armor and thence to the wearer. A 190-pound man would be given a backward velocity of about an inch per second, a motion that can be generally accommodated.

The kinetic energy component represents a much more severe problem. Whereas momentum is conserved in the interaction, the kinetic energy is primarily dissipated in the form of work. Three different mechanisms account for most of this dissipation:

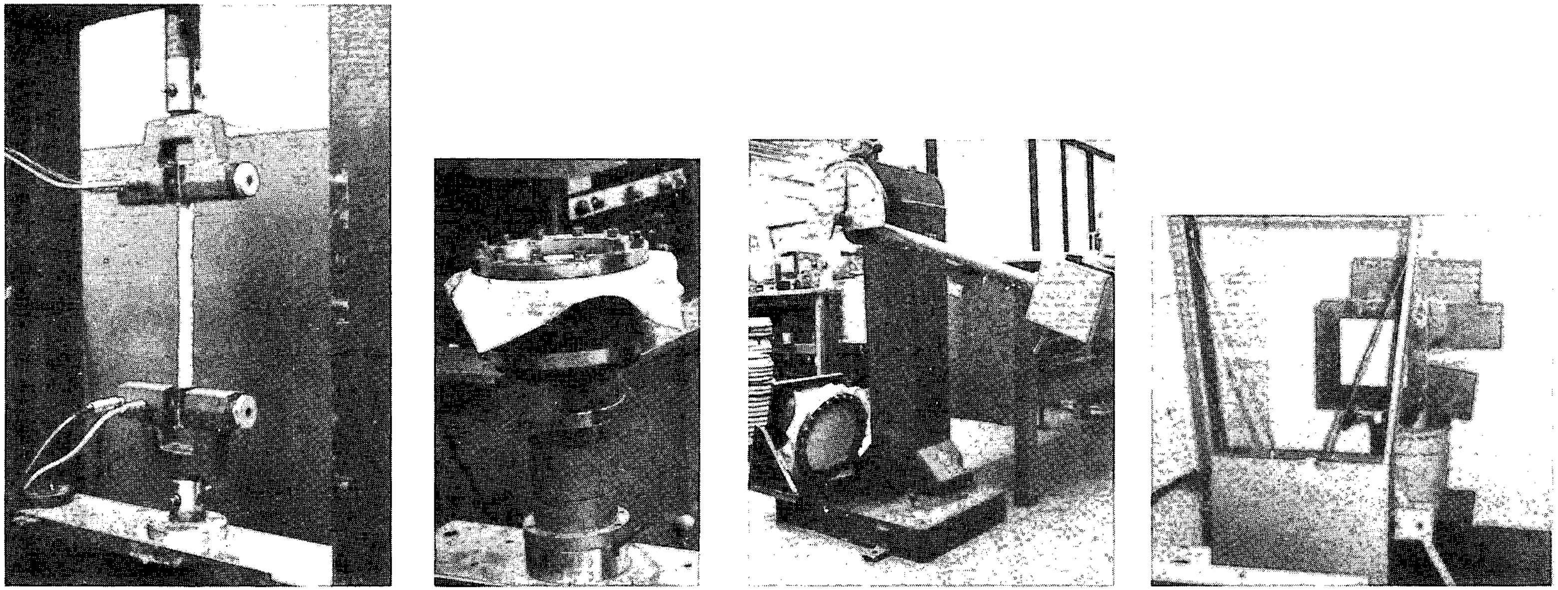
- Deformation of the bullet itself
- Deflection and deformation of the protective armor fabric (including fiber breakage, when it occurs)
- Deformation and deflection of the backing behind the protective armor

The actual distribution of absorbed kinetic energy among these three mechanisms depends upon their mutual interaction. For example, consider a fabric with a sufficient number of plies to prevent bullet penetration, held in a suitable test frame with only air as a backing. Even though a large fabric displacement occurs upon bullet impact, a negligible amount of energy is used to displace the air. Thus, virtually all of the energy is dissipated in bullet and fabric deformation. A denser and more viscous backing material, such as gelatin or clay, will absorb a significant amount of the bullet's energy in being displaced, causing less strain on the protecting fabric.

b. Bullet deformation. The bullet parameters affecting energy transfer to the protected target are diameter (caliber), mass, velocity, shape, and hardness (including jacketing). Given bullet mass and velocity, its kinetic energy and momentum are known (see Section IV. B. 2. a), and the resulting force exerted on the target depends primarily on diameter, shape, and hardness. A flat-nose wad cutter distributes its force over a large area, intercepting many yarns upon impact. Relatively low pressure (force per unit area) is consequently exerted on the yarns, and the protective armor more easily prevents penetration. On the other hand, the pressure directly under a round-nose, soft-lead bullet would initially be relatively high. However, due to the soft lead, the bullet mushrooms upon impact and its force is spread over a larger area, thus loading additional yarns and lowering the pressure. With jacketed bullets, expansion upon impact is inhibited by the hard copper or steel jacket. Thus, the armor loading is localized and high pressure on the protective armor results. In all cases, penetration occurs due to failure of the yarns exposed to impact and a pushing aside of adjacent yarns.

In order to establish the portion of bullet kinetic energy absorbed in bullet deformation upon impact, several sample bullets were mounted in an Instron testing machine (a static, uniaxial, material evaluation tool), which is shown in Figure 17(a). The bullets were then deformed to approximately the same shape by steady loading as resulted from ballistic impact with soft armor and both gelatin and clay backing. Between 10 to 20 foot-pounds of energy were required. This represents less than 10% of the total energy absorbed upon impact.

c. Backing deformation. Because the energy absorbed in the plastic deformation of the lead bullet is less than 10% of its total energy, the remaining energy must be absorbed in stretching the protective fabric, deforming the body of the wearer, and imparting backward motion to the wearer. The function of the protective material is obviously to prevent bullet penetration



(a) Instron
Static, uniaxial

(b) Indentor
Static, biaxial

(c) Charpy
Dynamic, biaxial

(d) Ballistic
Dynamic, biaxial

Figure 17. Materials Testing Devices Used in Laboratory Assessment of the Ballistic Protective Process

and to simultaneously distribute its residual energy over as large a surface of the backing material (the body) as is possible. The magnitude of this residual energy and the extent of its distribution is to a degree dependent upon the backing material itself.

The human body constitutes an extremely complex backing material and its exact simulation has, as yet, not been achieved. The approach in this program was, therefore, to choose backing materials with known properties that bracket the resistance range provided by the human body. The materials utilized were gelatin and an oil-base modeling clay. Gelatin is a highly elastic material that exhibits almost total recovery following deformation, and it has been used successfully for studying both ballistic penetration and blunt trauma in living tissue. Clay is a highly plastic material that undergoes viscous flow when deformed, is not strain-rate dependent, and exhibits very little recovery capability following deformation. As previously mentioned, analysis of the clay cavities formed during impact does not require sophisticated measuring and photographic equipment. It was recognized that although these two backing materials probably bound the general backing characteristics of many areas of the human body, bony areas such as the rib cage might not be represented.

Some consideration was also given to duct seal as a backing material. Duct seal is a low molecular weight polyisobutylene material filled with asbestos fibers and bentonite clay that exhibits a highly nonlinear viscoelastic behavior somewhat analogous to "silly putty." The response of such a material is very sensitive to bullet velocity and appears to have a high springback factor. Moreover, during ballistic tests, duct seal formed significantly smaller cavities in the backing material than either gelatin or clay, thus leading to a less discriminating assessment capability of blunt trauma effects. Its use as a backing material is therefore not recommended.

To illustrate the effect of backing material, dynamic indentation tests were performed with air, clay, and gelatin backing on a Charpy testing machine (a dynamic, biaxial pendulum impact tester), which is shown in Figure 17(c). The loading energy at which fabric penetration of a bullet-shaped steel indentor mounted on the pendulum initially occurred was established as a function of the number of plies of protective fabric (Figure 18). With air as the backing material, most of the residual energy is absorbed by the protective fabric and penetration occurred at low energy levels. Clay, on the other hand, deforms plastically and provides a much greater level of energy absorption. Gelatin simulates human tissue better than either air or clay, deforms elastically, and exhibits energy absorption characteristics between air and clay. As anticipated, the penetration energy with a given backing generally increases with the number of plies.

It should be noted that a relatively rigid backing, such as bone, would probably result in most of the bullet kinetic energy being dissipated in bullet and backing deformation since the protective fabric would be only slightly deformed, if at all.

d. Protective armor deformation. The influence of soft armor properties on the transfer of bullet kinetic energy can be better understood by first considering a very loosely woven fabric where a .38 caliber bullet can

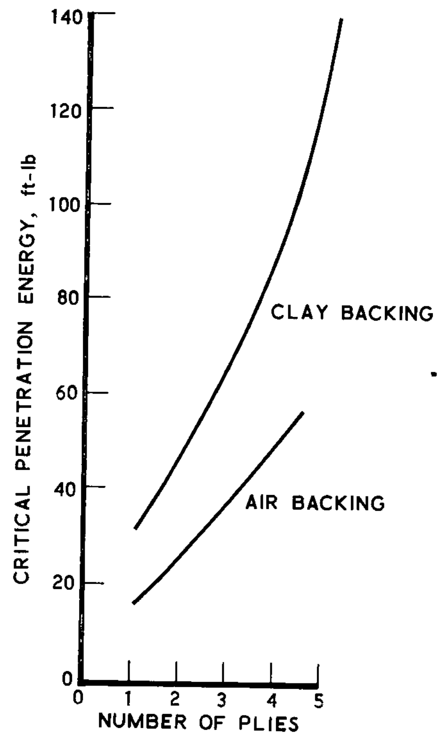


Figure 18. Effect of Backing Material and Number of Plies on Penetration Energy for Kevlar Fabric

easily pass through the fabric without intercepting any yarns. In this case, the armor absorbs no energy, and all of the bullet kinetic energy is dissipated in bullet deformation and penetration and deformation of the backing. If the weave of the fabric is progressively tightened, the .38 caliber bullet will interact with an increasing number of yarns and will ultimately be intercepted and defeated by the armor. At this point, a smaller diameter bullet, such as a .22 caliber bullet, may still find holes in the weave especially if the fabric is stretched or if loosely woven yarns slip and are pushed aside. Thus, the apparent anomaly where only 3 plies of Kevlar were able to defeat a .38 caliber bullet and 7 plies were required to defeat a lower energy .22 caliber bullet can be understood.

Soft armor fabric clearly acts as a net that intercepts the bullet without penetration. Because Kevlar is one of the strongest available synthetic fibers, its success in this application is understandable. However, not only the yarn but also fabric parameters must be considered. The yarn configuration, tightness or density of weave, yarn diameter (denier), yarn twist, and the frictional characteristic between yarns all influence Kevlar garment protective capability.

The optimum ballistic fabric would consist of the lowest denier, untwisted yarn in the tightest simple weave possible (one over, one under) and no yarn or fabric coating with lubricating qualities. A tight, simple weave is most effective in spreading the load to adjacent fibers. Low denier, untwisted yarn forms smaller cavities at the weave crossover points and discourages yarn separation and bullet penetration. Finally, lubricated yarns aid yarn separation, thus explaining the poor ballistic resistance of wet Kevlar even though the fiber strength is virtually unaffected.

With bullet penetration through the weave prevented, the penetration that does occur is the result of fiber failure. This latter process absorbs considerably more of the bullet's kinetic energy than does the slipping through process. This hypothesis was experimentally confirmed with ballistic tests of a 200 denier, simply woven fabric of 90 by 110 yarns (pics) per inch (see Figure 12).

Six plies of this fabric defeated both .38 and .22 caliber bullets at 800 and 1000 feet per second, respectively. Moreover, the .22 caliber bullet mushroomed and bounced off the first ply in the same way as did the .38 caliber bullet. Since the .22 caliber bullet penetrated several plies of 6-ply 400 and 6-ply 1000 denier fabrics, it was concluded that the tighter weave caused a .22 caliber bullet to behave upon impact in the same way as the .38 caliber bullet. Unfortunately, the finer denier Kevlar yarns have higher cost, appear more sensitive to environmental degradation, and result in larger deformation cavities following ballistic impact. As a result, the 400 denier baseline fabric was selected for subsequent garment fabrication as a compromise among numerous desired fabric characteristics.

3. Kevlar fabric testing. The response of the woven fabric to an applied load is markedly different from the response of a single yarn. A single yarn of Kevlar-29 exhibits an essentially linear stress-strain behavior to failure (the stretch is almost directly proportional to the applied force). The stress-strain behavior of the fabric, however, is extremely nonlinear. This nonlinear behavior is caused by the initial crimp in the yarns introduced by the weaving operation. The present weaving process produces fabric in which the warp yarns are highly crimped relative to the fill yarns (i.e., the warp yarn loops over and under the relatively straight fill yarns). As a result, when the fabric is deformed due to ballistic loading, the fill yarns are stressed much sooner than the warp yarns. Ultimately, of course, even the warp yarns begin to show a more linear stress-strain characteristic. Ballistic failure is, therefore, first initiated in the fill yarns.

To provide additional insight on how the bullet penetrates Kevlar fabric and on possibilities for improving the weave as a means for achieving increased protection, laboratory characterization of Kevlar fabric was undertaken. Detailed results obtained are discussed in Appendix A of Volume III of this report. Highlights of this effort are summarized in the rest of this section.

a. Uniaxial tensile tests. Tensile tests on samples of Kevlar fabric were performed with a standard Instron testing machine [see Figure 17(a)] in the fill and warp directions as well as at 15, 30, and 45 degrees from the fill direction. The resulting stress-strain relation for the fill and warp directions (the two extremes) is shown in Figure 19 and clearly demonstrates the more rapid loading of the fill yarns.

b. Charpy impact tests. Similar observations were made after examination of the results of the Charpy Tester for incipient penetration of Kevlar fabric following impact loading with a bullet-shaped impactor (Figure 20). The fill yarns have already failed under tension due to the imposed load, whereas the warp yarns are still intact. The warp yarns have obviously not been stressed as much as the fill yarns nor have they absorbed as much of the load as have the fill yarns. Thus, it appears that a fabric having the tension forces in the warp and fill yarns more equally balanced during a ballistic impact should result in a more uniform and more effective distribution of stresses and should, therefore, be also capable of sustaining greater loads before failure.

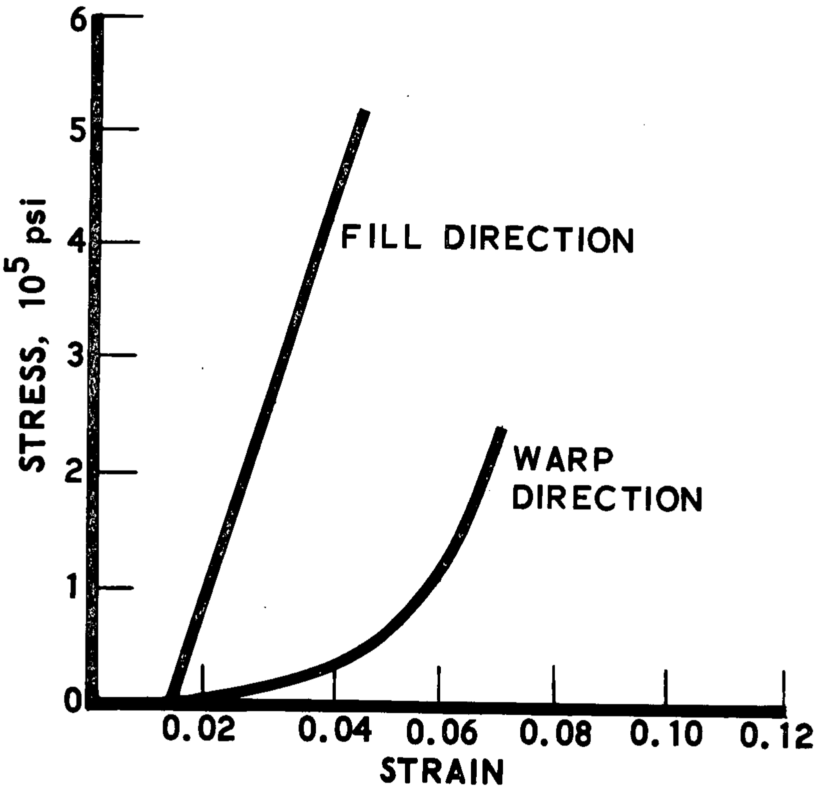


Figure 19. Tensile Test Results for Kevlar Fabric

c. Biaxial tests. Biaxial loading of fabric samples with an Instron Tester approaches the loading distribution imposed during bullet impact and was another of the laboratory techniques employed in studying Kevlar fabric behavior. The load was steadily applied to the center of an edge-restrained, 10-inch diameter fabric sample by means of an indentor shaped as a bullet [Figure 17(b)]. Both displacement and loading were continuously monitored until the fabric failed. Upon combining data obtained in this manner with similar data obtained under dynamic impact conditions with a Charpy Tester, it becomes possible to study the relative effect of changes in the number of plies and the effect of backing material on fabric deformation and indentor penetration.

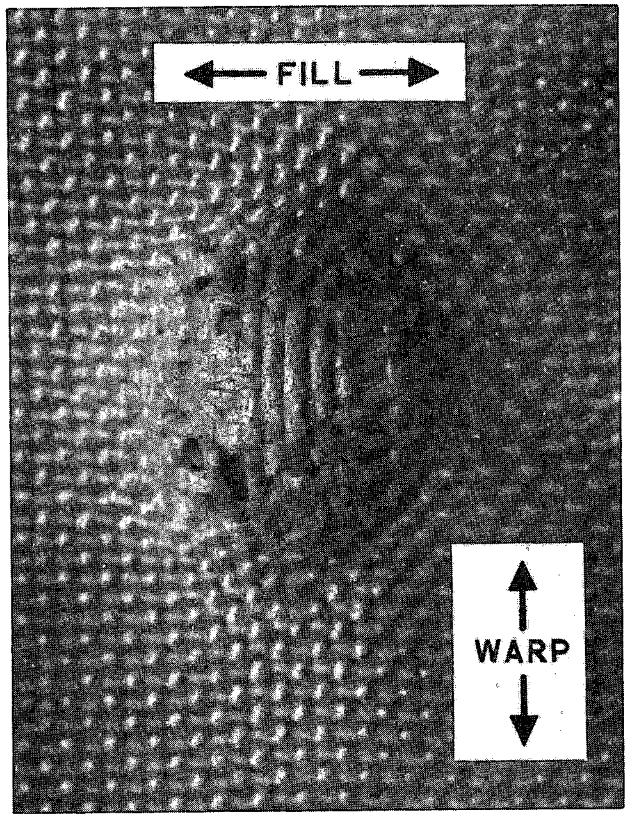


Figure 20. Incipient Penetration of Kevlar Fabric Under Charpy Dynamic Impact Loading

Such testing led to the conclusion that the protective capability of soft Kevlar armor does not increase linearly with the number of plies. It also appears that stitching multiple plies together provides some improvement over the unstitched case. It was also discovered that the presence of water (resulting from condensation on the cold gelatin backing block) degraded armor load-carrying capability.

It should be noted that small changes in armor performance can be easily detected in experiments of this type, because the forces and displacements involved can be accurately measured. Thus, the characterization of armor response under such controlled laboratory conditions offers valuable guidance for future armor development and improved analytical models.

d. Ballistic tests. The nonsimilar behavior of the warp and fill yarns previously mentioned is further apparent from frontal photographs of the bullet impact taken during ballistic testing of fabric samples [Figure 17(d)]. Time-phased high-speed photographs taken during bullet impact are shown in Figure 21. To improve the visualization of fabric deformation, concentric circles one centimeter apart had been painted around the target area.

Judging by the deformation of the painted pattern, the loading 100 microseconds after impact is only on the fill yarns (the horizontal fibers). Further loading begins to stress the warp (vertical) yarns as well, and by 500 microseconds after impact, a vertical as well as horizontal deformation of the pattern appears. By 960 microseconds after impact, these pattern deformations have taken on a clearly rectangular appearance. However, the horizontal dimension of this rectangle is significantly less than the vertical dimension, again suggesting that the fill fibers are more highly loaded than are the warp fibers.

A balanced weave (i.e., equal tension in both warp and fill fibers) should result in a square pattern throughout the impact period due to

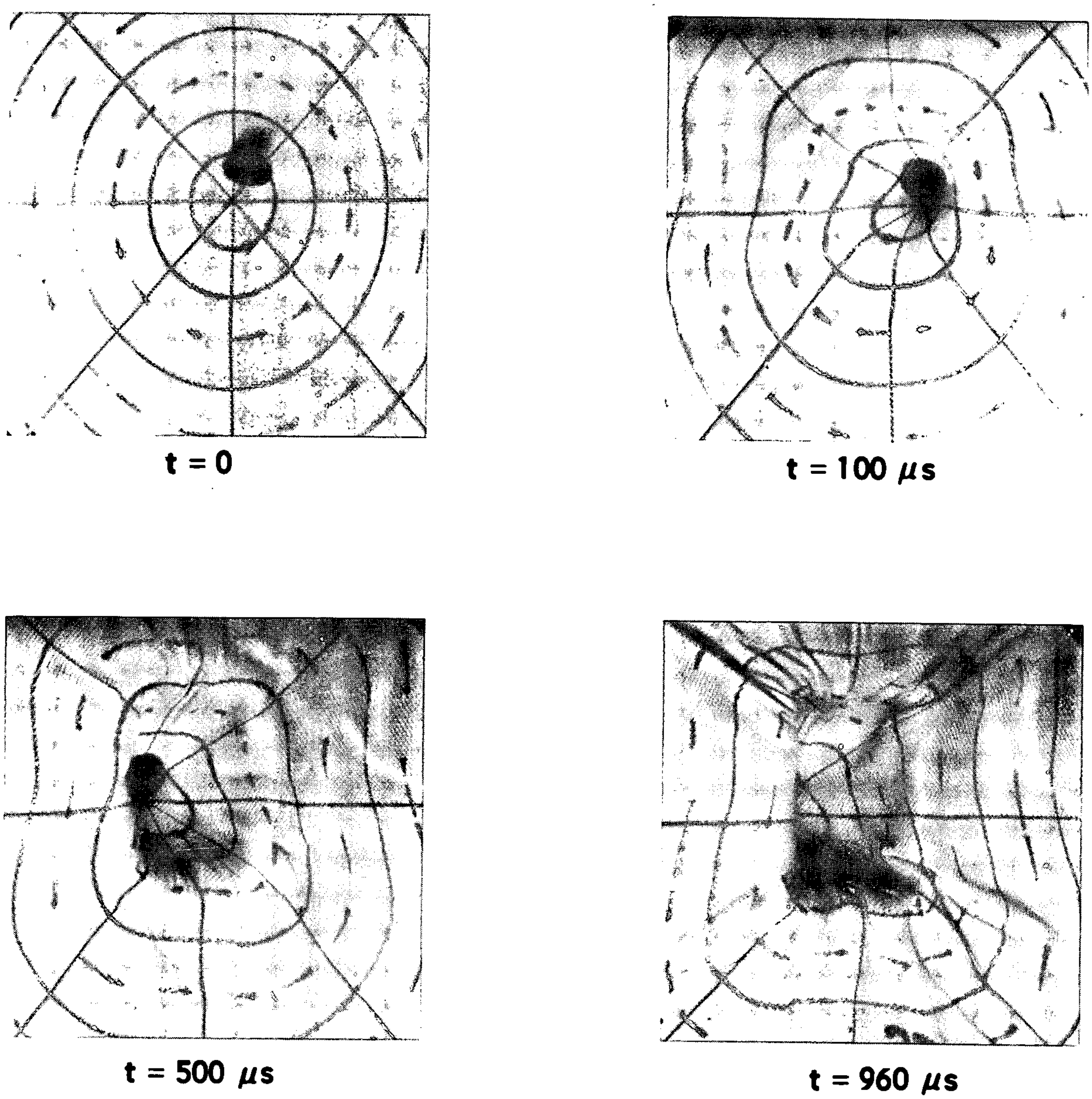


Figure 21. High-Speed Frontal Photographs of Kevlar Fabric Deformation Upon Ballistic Impact. (Gelatin backing; 7-ply Kevlar, 400/2 Denier, 36 × 36 weave; .38 caliber round-nose bullet)

the uniform warp and fill loading and, as previously mentioned, should maintain a greater load before failure.

e. Effect of bullet deformation. The results described in the preceding sections apply to a nondeforming or jacketed bullet. With deforming lead bullets, opposite failure mode results were encountered. Impact tests with soft, deforming indentors as well as ballistic tests with lead bullets where the first ply of a multi-ply fabric failed both gave similar results. The failure was usually initiated in the warp fibers rather than the fill fiber.

A possible explanation for this difference in failure mode is based on the fact that a lead bullet that impacts resisting Kevlar armor is deformed into an elliptical plan-form with the major axis in the warp direction (i.e., the direction of least resistance). Simultaneously, a mold of the fabric surface is formed on the bullet surface in contact with the fabric. Thus, as the bullet deforms in the warp direction, the fill fibers in mesh with the mold are spread by being forced to the sides of the bullet. The net result is that the load is imposed on the warp fibers, and when their capacity is exceeded, fabric failure results.

It should be noted that in this latter case as well, a balanced weave (equal tension in warp and fill fibers) is desirable and will improve the loading capacity of Kevlar fabric. Hence, the same solution appears valid whether the fabric fails initially from either fill yarn or warp yarn loading.

4. Blunt trauma evaluation. Body wall and underlying viscera deformation that occur following nonpenetrating bullet impact represent a

major consideration that influences the use of soft body armor. Neither experimental nor analytic techniques for backface simulation of the human body are, as yet, available. Consequently, current assessment of blunt trauma is essentially dependent upon qualitative experimental results based upon both biological and nonbiological procedures.

a. <u>Blunt trauma data correlation.</u> Under interagency agreement, the Edgewood Arsenal Biomedical Laboratory undertook assessment of the blunt trauma effects with soft body armor. Data from Army sources and published literature for projectile-induced blunt trauma on animals and humans were examined and evaluated. It was concluded that with a protective garment survival probability after a random hit in the protected area with a .38 caliber bullet would exceed 95%. It was further concluded that the probability of needing surgery, which exceeds 80% without the garment, is reduced to less than 10% when a protective garment is worn.

Additional discussion of the results obtained and the conclusions reached are included in the separately published U.S. Army report.[6]

b. <u>Assaults on protected officers.</u> During mid-1974, three California police officers were shot with handguns in separate incidents while wearing commercially available vests of 18-ply ballistic nylon. All three of these cases were investigated immediately by Aerospace personnel and a medical consultant. One was shot in the chest area with a .32 caliber automatic and the others were shot in the chest area with .38 specials. In all three cases, there was high probability that the wound would have been fatal without the protective garment. Instead, each officer was immediately able to defend himself, returning the gunfire in two of the three cases. The blunt trauma wound behind the point of impact was similar in all three cases, namely, an abrasion that developed into a 2- to 3-inch bruise. A more complete discussion of each incident is presented in Appendix B of this volume.

Subsequent to the assaults, samples of the nylon material used in the protective vests involved in these incidents were obtained and subjected to ballistic tests simulating the actual assault conditions. These results were compared to identical tests of Kevlar fabric, and it was concluded that seven plies of Kevlar offered essentially the same penetration protection at about one quarter the weight. A valid blunt trauma comparison could not be made.

5. Observations and recommendations. The insight acquired from the laboratory tests discussed in this section not only provided important guidance for improved fabric development and for achieving more effective ballistic protection, but also aided in identifying several other protective applications for Kevlar, which are discussed in Appendix C of this volume. More specifically, the dynamic indentation tests, for example, improved the understanding of the energy transmitted through the protective fabric and into the backing material. This issue represents a major concern of soft armor designers. However, as is often the case, some answers are provided while additional issues are simultaneously raised. Suggestions for the examination of such remaining questions are presented in the paragraphs that follow.

- Kevlar-29 fabric currently exhibits extreme anisotropy due to the weaving technique utilized. A woven fabric having approximately equal crimp in both the warp and fill directions without reducing fabric density (yarns per inch) should significantly improve penetration resistance and reduce the imposed blunt trauma. A comprehensive study of weaving parameters, including initial yarn tension, the effect of yarn twist, and the effect of yarn coatings and the resulting lubrication, is needed.

- Since 2 plies of fabric displayed less than twice the penetration resistance of a single ply, techniques should be sought to raise the effectiveness of multi-ply fabrics. Techniques, including quilting which appeared to offer promise, as well as angular orientation of adjacent plies and denier and weave changes between adjacent plies should be considered.
- Kevlar-29 fabric was chosen for its flexibility and potential comfort and inconspicuousness. It clearly lacks the characteristics inherent in ceramic and rigid composite armors that prevent localized blunt trauma and provide for dissipation of bullet energy over a wider area of the body. A composite material retaining the advantages of both types of armor is desirable. The combination of Kevlar and other materials that have a time or rate dependent loading response (analogous to "silly putty") offers interesting possibilities. The composite would be flexible under the low strain rates of normal wear but locally rigid under

high strain rates such as accompanying ballistic loading. All elastomers (rubber-like materials) also exhibit rate-dependent strain behavior and should be considered not only for composite use but as coating materials as well.

- Multidimensional fabric weaves (three-dimensional, tri-axial) have received attention as part of the Department of Defense missile reentry program. The penetration resistance and blunt trauma transmission of such fabrics should be compared to the currently available two-dimensional protective garment weaves.
- It was established that water significantly degrades the penetration resistance of Kevlar-29 fabric. The effect of humidity, although treated in Section IV. C, remains to be more fully assessed. Additional assessment of waterproof coatings as well as a better understanding of the action of humidity and material coating on the bullet penetration mechanism is needed.
- A portion of the Edgewood Arsenal soft armor program involved animal testing. The objective of those tests was to study the effect of blunt trauma on living organs and to provide guidance for developing a soft armor/blunt trauma analytical model. Due to a general inadequacy of previous information and the limited scope of that program, it is still not possible to correlate the current findings to human

beings. Future effort on soft body armor should consider the development of an empirical model for blunt trauma from which human experience can be predicted by simple, nonbiological laboratory testing of armor samples.

C. Environmental Testing

Since virtually no information regarding the effect of environmental exposure on woven Kevlar fabric was available, Aerospace initiated a preliminary environmental assessment program as an aid in guiding the subsequent garment development effort, the prototype garment operational wearability tests, and the more extensive environmental test program at Edgewood Arsenal.

Highly oriented synthetic fibers, such as Kevler-29, are generally more susceptable to chemical degradation than the parent material in the bulk form. The lower resistance of the fiber to chemical degradation is caused by the molecular alignment that results when the fiber is drawn. A classic example of this phenomenon is the rapid deterioration by ozone attack of a stretched rubber band relative to an unstretched rubber band. In the former, molecular alignment results from the stretching process. In addition, clothing is routinely exposed to harsh wearing and cleaning environments.

Because of the concern that significant degradation of a Kevlar protective garment might occur during normal use, the effects on the fabric of laundering, dry cleaning, ozone, salt water, and humidity were investigated.

Complementary environmental effects test results obtained at Edgewood Arsenal are separately reported in Reference 6.

1. Procedure. The environments examined were those most likely to be encountered during normal wear. Four exposure cycles were used (standard tests typically require 25 cycles). When extreme degradation resulted, additional testing was not pursued. However, where only minor or no degradation was observed additional testing was performed.

After exposure to the selected environment, ballistic tests with .38 and .22 caliber handguns and laboratory mechanical tests (tensile and dynamic impact) were performed.

2. Salt solution exposure. Because the protective garments being considered include undergarment designs, the effect of perspiration on Kevlar fabric is of obvious interest. A single ply of Kevlar-29 400/2 (36 $\times$ 36) fabric was soaked in a 3% salt (NaCl) solution for 48 hours at room temperature to simulate exposure to wearer perspiration. The specimen was then dried in air and sunlight, and tensile tests performed on both the fabric and on a single strand of yarn. No degradation as a result of the salt water exposure was detected in either test.

3. Ozone exposure. A cursory check on ozone attack of Kevlar-29 was made by exposing single-ply samples of 400/2 (36 $\times$ 36) fabric to an ozone concentration of approximately 200 parts per million for a period of 6 hours. This concentration represents a level more than 200 times the normal concentration in Los Angeles, California. Subsequent single-yarn tensile tests revealed no degradation as a result of this exposure.

4. Water and humidity. All-weather wearing of protective garments can cause them to be exposed to excessively humid conditions as well as rainy weather. Any degradation in the ballistic protection that may occur as a consequence of such exposure is obviously of major concern.

Tensile tests of 400/2 (36 × 36) fabric immediately after quenching in water indicated an approximately 6% degradation in both the warp and fill directions. Moreover, as mentioned in Sections IV. B. 2. d and IV. B. 3. c, the lubrication water provides adjacent yarns severely degrades penetration resistance.

To provide a more complete assessment of the effect of water on the ballistic degradation of Kevlar-29 fabric, a series of firings were made with both .38 and .22 caliber weapons at 7-ply, 400/2 (36 × 36) Kevlar-29 samples that had been exposed to various types of wetting. The results are summarized in Table 10. Also presented in Table 10 are results of ballistic tests with a dry fabric sample and with wet samples protected by a water-proofing coating.

The 100% humidity tests were accomplished by suspending the fabric sample over water in a sealed polyethylene bag at room temperature for 24 hours. Ballistic tests were then performed without removing the specimen from the bag. Tests of the wet samples were made after the samples had been briefly immersed in water. More thorough soaking for varying time periods was also assessed. The absorption of water into the fabric was almost instantaneous and resulted in a severe degradation of ballistic resistance. After only a 20-minute soak, the 7-ply fabric was

Table 10. Ballistic Tests of Water-Wetted Fabric [7-ply, 400/2 (36 × 36) Kevlar-29]

Exposure		Backing	Results
.38 caliber, 158 grain, 875 ± 20 feet per second			
Dry		Clay	No penetration
100% Humidity		Clay	No penetration
Wet		Clay	Complete penetration
Wet		Rubber Dummy	Complete penetration
Soaked:	2 minutes 3 minutes	Clay Clay	Partial penetration - four plies (Broke all seven plies)
	20 minutes	Clay	Complete penetration
	1 hour	Clay	Complete penetration
Coated with Scotch Guard:			
	100% humidity	Clay	No penetration
	Wet	Clay	Partial penetration (Broke all seven plies)
.22 caliber, 40 grain, 985 ± 25 feet per second			
Dry		Clay	No penetration
100% humidity		Clay	Partial penetration
Wet		Clay	Complete penetration
Coated with Scotch Guard:			
	Wet	Clay	Complete penetration (3 out of 4 times)

completely penetrated by the .38 caliber bullet. In the dry condition, only three plies were needed to defeat this same threat.

Examination of the fabric samples that failed when wet did not reveal any fracture of the individual fibers. Instead, adjacent fibers had been spread apart and a hole created for the penetrating bullet. As previously mentioned, the wetting by water appeared to lubricate the individual fibers, reducing the friction between fibers and allowing sufficient fiber displacement to accommodate bullet penetration.

Exposure to high humidity for 24 hours did not result in as severe a degradation as wetting. No penetration occurred with a .38 caliber bullet and only partial penetration resulted with a .22 caliber bullet. It was nevertheless concluded that any wetting of Kevlar-29 protective fabric is undesirable and should be avoided. Since some benefit was suggested by U.S. Army results with waterproof coatings,[6] a few preliminary tests were made of fabric samples having each individual ply coated with Scotch Guard. Although some benefit in reducing the ballistic degradation of the fabric when wet was observed, severe degradation did, nevertheless, occur. Subsequent additional tests by Edgewood and Aerospace indicated that commercial waterproof coatings such as "Zepel" can minimize the wet fabric ballistic degradation to acceptable levels.

5. Laundering or dry cleaning. It is intended that protective garments be worn routinely and in many cases adjacent to the body. Thus, numerous launderings or dry cleanings would be required during the life of the garment. This exposure can represent a serious problem if garment degradation

is encountered . Accordingly, an exploratory evaluation involving a variety of laundering/cleaning procedures was undertaken.

a. Test procedure. Ten-inch square test panels of 400/2 (36 × 36) and 1000/1 (31 × 31) Kevlar-29 fabric sewn around the edges were washed in several ways in a standard agitator-type household washing machine (Maytag). Drying involved the use of a standard, tumble-type dryer (Cissell Corporation). Ballistic and tensile tests were performed after exposing the fabric specimens to four complete washing and drying cycles.

The single dry cleaning solvent assessed was percholorethylene, and fabric specimens were also exposed to four complete cleaning cycles.

b. Tensile test results. A summary of the degradation resulting in the tensile strength of the fabric samples in both warp and fill directions for the variety of washing/cleaning techniques examined is given in Table 11. For purposes of comparison, the degradation of a wetted 400/2 (36 × 36) sample, quenched in water just prior to testing is also given.

With the 400/2 (36 × 36) material, both washing and cleaning yield greater degradation in the fill yarns. Using a soap appears to cause additional degradation over both the wetted material and soapless washing cases. A hot water/Ivory wash or a cold water/Woolite wash offer least fabric degradation. Further, it appears that garment cleaning with perchloroethylene would also result in acceptable degradation levels.

c. Ballistic test results for washed/cleaned fabric. An overview of the ballistic degradation that occurred with the variety of washing/cleaning techniques examined is given in Table 12. Data for both .38 and

Table 11. Fabric Degradation Due to Washing and Cleaning

Exposure	Tensile Degradation (%)	
	Warp	Fill
Washing		
400/2 denier (36x36 yarns per inch)		
Wetted material (quenched prior to testing)	6.3	6.1
Cold water wash	0	-
Hot water wash	5.6	-
Hot water + Tide	8.4	18.8
Hot water + Ivory	7.7	18.9
Cold water + Woolite	7.65	18.8
Cold water + All	12.8	25.1
Cleaning		
Cleaned with Perchloroethylene	3.4	5.7

.22 caliber test firings are included. For purposes of comparison, the test results with virgin fabric are also given.

No penetration occurred with virgin material (unwashed and uncleaned) for the .38 caliber firings. Moreover, after a sequence of four separate washings with either Tide, All, or Tide plus Clorox, or four separate cleaning cycles with Perchloroethylene, .38 caliber penetration was still prevented. This is not to say that washing or cleaning did not degrade

Table 12. Ballistic Tests of Washed/Cleaned Fabric. [7-ply 400/2 (36 × 36) Kevlar; rubber dummy backing]

Exposure	Velocity (ft/sec)	Result
.38 caliber; 158 grain		
Virgin material	725 ± 20	No penetration
Hot water + Tide	725 ± 20	No penetration
Cold water + All	725 ± 20	No penetration
Hot water + Tide + Clorox	725 ± 20	No penetration
Dry clean with perchloroethylene	725 ± 20	No penetration
.22 caliber; 40 grain		
Virgin material	945	Partial penetration
	830	Partial penetration
	999	Complete penetration, stopped in 6th and 7th plies
Hot water + Tide + Clorox	1000	Complete penetration
	936	Complete penetration, stopped in 7th ply
	961	Partial penetration
Cold water + All	1000	Partial penetration
	920	Complete penetration, stopped in 7th ply
	1008	Complete penetration, stopped in 7th ply
Hot water + Tide	1013	Partial penetration
	965	Partial penetration
	948	Partial penetration
Dry clean with perchloroethylene	1004	Partial penetration, stopped between 6th and 7th ply; ruptured 7th ply fibers
	960	Complete penetration, stopped in 7th ply
	982	Complete penetration, stopped in 7th ply

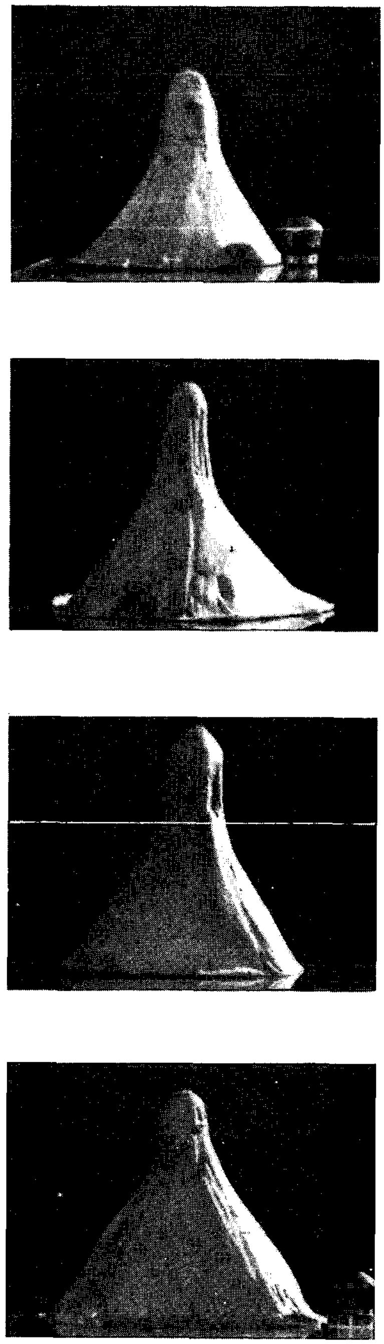
the fabric, but rather that the degradation that did occur remained within the penetration-prevention capability of the fabric.

A somewhat different situation existed for the .22 caliber threat. The virgin material is partially penetrated by a .22 caliber bullet, and the washing/cleaning process degrades the material further. Thus, after four repeated washings or cleanings, complete penetration frequency occurs. Only washing with hot water and Tide limited the degradation to partial penetration and avoided complete bullet penetration into the backing material. Further, the use of Clorox in the laundering process appears to accelerate the degradation introduced by soap and hot water alone.

Caution should be exercised in extrapolating these observations, which are based on limited testing, to general conclusions. Considerably more testing is needed before general laundering/cleaning recommendations can be confidently provided.

A visual approach to assessing the ballistic degradation introduced by laundering was attempted by making epoxy molds of the cavity created in the clay backing. Photographs of four such molds are presented in Figure 22 and show the comparative protective fabric deformation due to washing with hot and cold water. When the material is washed, the depth of bullet penetration increases, indicating a loss in fabric strength. A hot wash appears to be more severe than a cold wash, and a combined cold and hot dry air temperature cycle appears to produce the severest degradation of all.

6. Summary of results. A summary of the results of the Aerospace environmental tests on Kevlar-29 as augmented by results of complementary



(a) Virgin Material

(b) Hot Wash

(c) Cold Wash

(d) Dry-Air Hot and Cold Temperature Cycle

Figure 22. Increase in Ballistic Test Clay Backing Cavity Size due to Washing. [8-ply 200/1 (61 × 63) Kevlar-29 fabric; .38 caliber, 158 grain bullet, 780 ± 20 feet per second]

tests performed by the U.S. Army is given in Table 13. Limited exposure to salt spray, sunlight, and ozone caused no problem. Very high humidity may introduce some material degradation. Complete wetting causes serious degradation. Consequently, an appropriate water repellent coating appears necessary.

Certain dry cleaning solvents and soap detergents as well as household bleaches significantly degrade the material. For the present, it is recommended that cold-water Woolite or Ivory soap be used for machine washing and that an air drying cycle be utilized. For dry cleaning, perchloroethylene, a cleaner used with high-quality knitted fabrics, is suggested.

7. Recommendations. It is strongly recommended that additional environmental testing be performed. The ballistic sensitivity of Kevlar to wetting by water is of special concern, and a more complete assessment is needed in order to define with confidence the extent to which such exposure can be accepted. Rain, body moisture, and laundering/cleaning cause exposure to water and unfortunately also represent frequent environments to which the garments are subjected. Providing the garment with a water repellent coating appears beneficial; however, degradation of coated Kevlar fabric with normal wear needs further assessment.

D. Garment Concept Evaluation

The initial attempts at fabricating Kevlar protective garments occurred during FY 1973 in the early phases of this program. The U. S. Army Land Warfare Laboratory was responsible for fabricating several vests and sport

Table 13. Summary of Kevlar-29 Environmental Test Results

Environment	Exposure	Test Method[a]	Results/ Recommendations
• Cleaning-Washing and drying	Washing and drying under normal conditions	Mechanical/ballistic	Detergents and bleach degrade fabric severely. Use cold water Woolite and air dry cycle
• Cleaning-dry cleaning	Commercial cleaning procedure	Mechanical/ballistic	Only perchloroethylene solvent did not degrade fabric (double knits).
• Salt spray	3% salt solution 48 hours (simulate perspiration)	Mechanical/ballistic	No degradation to fabric.
• Sunlight	34 hours	Ballistic	No degradation to fabric
• Ozone and ozone/ultraviolet	72 hours at extreme conditions	Mechanical/ballistic	No degradation to fabric
• Humidity	100% relative humidity at room temperature for 48 hours	Ballistic	Minor cavity degradation.
• Water immersion	Total immersion 10 minutes	Ballistic	Significant degradation; waterproofing may be required

[a] Mechanical Test
Instron tensile
Charpy impact

Ballistic Test
.38 caliber bullet
.22 caliber bullet

jackets, and The Aerospace Corporation contracted for several police uniform garments including a New York Police Department reefer coat with a removable lining. For the sport jacket, Kevlar was inserted as a filler between the outer material and the lining, with five plies of Kevlar used on the right side of the jacket and ten plies on the left. No Kevlar was used in the sleeves. The reefer coat lining was replaced with a 5-ply Kevlar lining. Heavy duty cutting and sewing equipment was used in working with Kevlar, and no major problems were encountered in modifying the garments.

Visual inspection of early samples of woven Kevlar fabric procured for these garments revealed inadequate quality control during the weaving operation. Consequently, as indicated in Section IV. A. 3, The Aerospace Corporation, in conjunction with DuPont and the Natick Laboratory, produced a weaving specification incorporating visual and mechanical inspection techniques to ensure appropriate quality control. Based upon these revised specifications, fabric was procured for use in the protective garments fabricated for the preliminary wearability tests described in Section IV. E.

Prior to initiating the design and procurement of the garments for the preliminary wearability tests, the two prototype garments were exhibited to LEAA Regional Offices and also demonstrated to potential users for comment and reaction. The design suggestions and desired garment features offered by police and federal law enforcement agencies, by police uniform and protective armor manufacturers, and by other participants in this program were examined and assessed. These suggestions and features were included in subsequent garment designs where appropriate and feasible.

E. Prototype Garment Development

Once the feasibility of incorporating Kevlar fabric into a garment had been successfully demonstrated, the next phase in the development effort was initiated. This involved designing and fabricating various styles of prototype protective garments to be used in assessing their acceptability to law enforcement agencies. In some cases, new garment concepts were introduced, and a series of iterative steps leading to the final garment designs were required. In other cases, existing police uniform components were modified to accept a Kevlar lining. A 7-ply, 400/2 (36 × 36) Kevlar-29 material was used in all garments.

Before proceding with any protective garment design effort, extensive discussions were held with uniform and body armor manufacturers. Most of these companies voiced interest in the technology being developed but did not consider it economically feasible for them to become involved in fabricating a small-volume order of prototype garments. However, recommendations were offered for two companies in the Los Angeles area (Transcon Manufacturers and E&E Fabratex) who had experience acquired through military and civilian contracts, and the capability (cutting equipment, heavy duty sewing machines, etc.) to assist in the design and fabrication of prototype protective garments. In addition, Rochester Coat Makers, an experienced tailoring concern in the Los Angeles area, was willing to experimentally fabricate some civilian-styled protective sport coats and vests.

The services of these three organizations were acquired for the design and fabrication of prototype garments. Three basic garment categories were considered, namely, special accessories, police uniform components, and civilian garments, and over 70 individual garments were designed, fabricated, and assessed. Much background information and guidance was provided by Lt. Lief Reinertson, head of the New York Police Department Equipment Section, during this phase of the program.

1. Special accessories. Two general garment types were developed under the Special Accessories category: undergarments and outer vests.

a. Undergarments. Undergarments were expected to be the most widely applicable protective garment for law enforcement personnel, and major attention was focused on this category. Designs for continuous wear, inconspicuous undergarments were developed, fabricated, and iteratively modified according to wearer reactions.

Two different short undergarment designs were ultimately developed: the closed-side design shown in Figure 23(a), and the open-side design, shown in Figure 23(b). The former provided side as well as front and back protection, and included a "shirttail" to aid in anchoring the garment and to keep it from riding up on the wearer. The latter design was a much looser fitting garment to provide for improved wearer comfort. It consisted of front and back panels connected by shoulder straps and featured side openings for cooling air circulation. Such two-piece construction also allows fit adjustment over a range of wearer sizes but does, of course, introduce somewhat less protective coverage.

(a) Closed-Side Short Undergarment with Cotton Skirt

(b) Open-Side Short Undergarment

(c) Women's Undergarment

Figure 23. Prototype Kevlar Undergarments

To improve the protection provided by the short undergarment design, a body shirt protective garment was also fabricated. The front protective coverage was extended to the crotch area, and the back panel was extended to slightly above the pelvic bone. Provision was made to relieve the body-restraining forces when sitting or bending over. It was quickly determined that when made of Kevlar such a garment is bulky and uncomfortable to wear, and further effort on this design was discontinued.

In response to the need for providing protection to the increasing number of policewomen, the design and fabrication of a protective undergarment for women was also undertaken. The resulting garment, which is shown in Figure 23(c), has received some assessment, and suggestions for improving the garment include changing to a pastel color and improving the comfort in the bust area. A fully satisfactory garment has not yet been designed.

Using the facilities (anatomical load analyzer) of the U.S. Army Natick Laboratory, data were obtained on forces acting on the body for selected protective undergarment designs. Such data were subsequently utilized to improve the design and fit.

Loads imposed on the body were measured while performing eight different psychomotor tasks. These were:

Standing	- At rest (reference case)
Standing	- Heavy breathing
Standing	- Stooped over
Rifle firing	- Standing

Rifle firing	- Kneeling
Reaching for holster	- Right hand to left side
Reaching up	- Both hands
Sitting	- Leaning back
Reaching forward	- Both hands

Typical load measurements for a short undershirt are given in Figure 24. Force data at four body locations for five of the positions tested are presented for the original garment and for the garment with the elastic interior webbing removed. This webbing had originally been included in the garment to provide the wearer with a tighter fit. Removal of the webbing reduced the wearer forces and improved comfort.

b. Outer vests. The outer vest is intended to be worn by a law enforcement officer only when an increased need for protection is anticipated. Typical situations include stopping a traffic violator, apprehending a suspect, or responding to a family quarrel. The garment would be carried in the patrol car in a convenient location and donned quickly when required. This type of garment is not intended to replace the high-threat ballistic vest used in many special police operations such as stakeouts or barricade incidents.

The design of the protective outer vest is similar to that of a flack jacket or commercially available hunting vests. This garment, which is shown in Figure 25(a), is intended to fit loosely over the normal police uniform. Nomex was used for the outer shell, which enclosed the seven layers of Kevlar. A front velcro, quick-closure design was utilized.

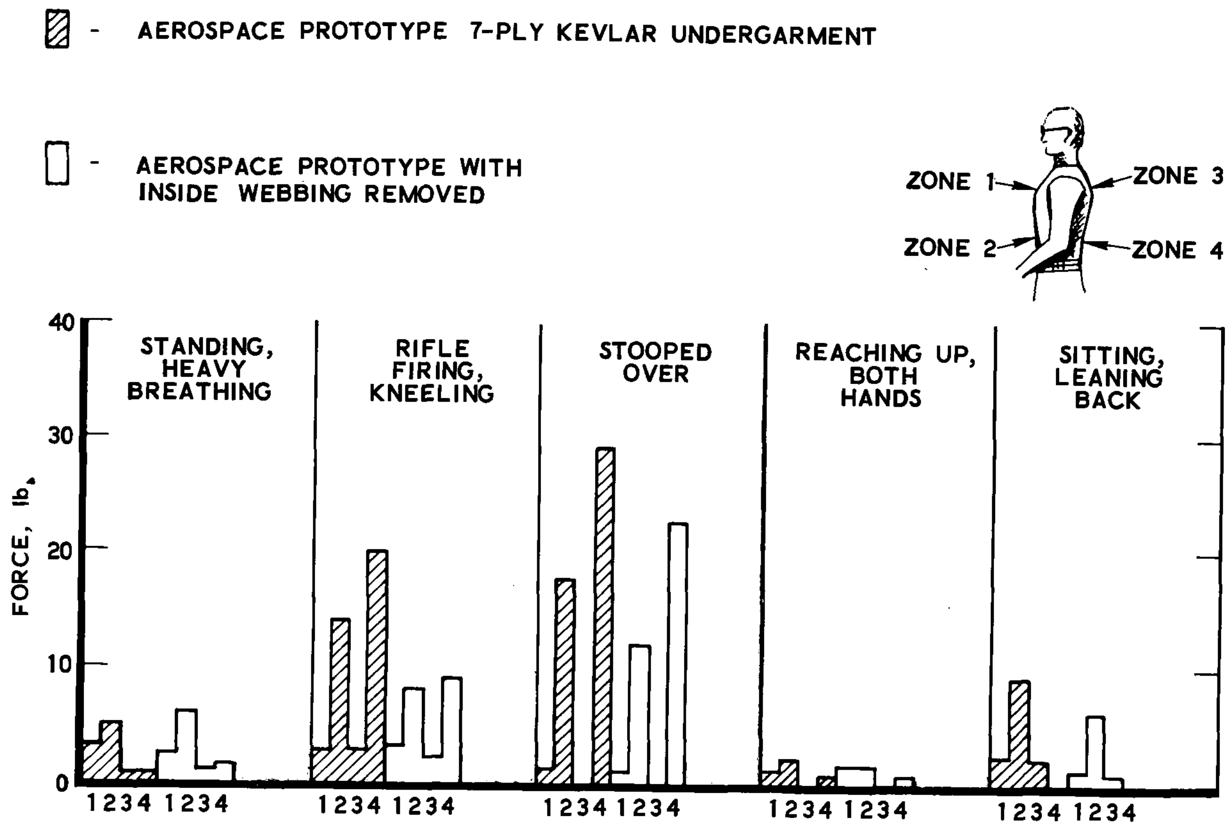


Figure 24. Typical Anatomical Load Measurements, U.S. Army Natick Laboratory Tests

Comments on the utility of the short vest design were generally favorable. Some concern was expressed that the vest covered the officer's identification (badge and nameplate), and future designs should incorporate such identification on the outside of the vest.

An alternate vest design providing greater torso protection (below the waist and in the groin area) than that of the short vest was also

(a) Short-Vest Design

(b) Long-Vest Design

Figure 25. Prototype Kevlar Outer Vests

fabricated, and is shown in Figure 25(b). The reaction to this design was also generally favorable.

2. Police uniform components. A wide variety of police uniform components were provided with Kevlar liners and a preliminary assessment was made of the feasibility of such protective garments. The original garments were procured from police uniform manufacturers or distributors and then modified to accept the Kevlar protective liner. Several different techniques for adding the Kevlar protection were utilized and evaluated. These included:

- Removable liners
- Sewing directly to the existing liner
- Restructuring the garment and inserting the Kevlar between the outer and inner shell.

All modified garments were assessed for comfort, wearability, and appearance, and preliminary comments were solicited from the police departments of New York City, and Culver City, Torrance, and El Segundo, California. The styles of police uniform to which protective material was added in the torso area are described in the paragraphs that follow. All photographs are of the modified garments.

a. Los Angeles Police Department leather motorcycle jacket, Figure 26(a). Because such jackets are designed to fit close to the body, it is current practice to custom fit every jacket purchased to the individual officer. The original jacket is rather heavy, and when protective material

(a) LAPD Motorcycle Jacket

(b) LAPD Vinyl Patrol Jacket

(c) NYPD Scooter Coat

(d) NYPD Officer's Coat

(e) NYPD Trooper Coat

(f) Chicago PD Cloth Jacket

Figure 26. Prototype Police Uniform Protective Garments

was added, the jacket became almost too heavy to be worn comfortably. A detachable liner design was used with this style jacket, but even then, because of the style and cut of this type of jacket, incorporating the protective liner was a difficult tailoring job.

b. Los Angeles Police Department vinyl patrol jacket, Figure 26(b). The fit of this jacket is somewhat looser than the leather motorcycle jacket and, as a result, adding a protective liner is less difficult. Both a detachable, snap-in Kevlar lining and a fully integrated Kevlar lining in place of the lining with which the jacket is supplied were developed. The latter design is preferred on the basis of appearance and comfort.

c. New York Police Department scooter coat, Figure 26(c). This particular garment style is a widely worn police coat. Both detachable and permanent Kevlar liner designs were fabricated. In the latter case, two alternative approaches were taken. In one, the protective material was sewn directly onto the existing garment liner, and in the other, the existing liner was removed and replaced with the protective material. Replacing the existing lining resulted in the best appearing and most comfortable garment.

d. New York Police Department officer's coat, Figure 26(d). The officer's winter coat used by the New York Police Department consists of a tailored woolen outer shell with a zip-in removable lining. A removable Kevlar lining was provided to replace the lining with which the coat was supplied. The resulting fit and comfort were considered satisfactory.

e. New York Police Department leather trooper jacket, Figure 26(e). This garment is a hip-length leather jacket with a permanent lining. A snap-in detachable Kevlar liner was added to one jacket, and in a second jacket, the commercially supplied lining was removed and replaced by an integral Kevlar lining permanently sewn into the jacket. Although the latter version of the jacket provided a better fit and was more comfortable to wear, both designs result in heavy jackets that were considered almost too heavy to be worn.

f. New York Police Department summer blouse. This summer blouse is a lightweight jacket with a below-the-hips length. As designed, it is provided with a zip-in light woolen lining and fits more loosely than do tailored jackets. A zip-in Kevlar lining was designed and fabricated to replace the normally supplied zip-in lining. The comfort and appearance of the garment with the Kevlar liner were considered acceptable.

g. Chicago Police Department cloth jacket, Figure 26(f). This cloth jacket is similar to the vinyl patrol jacket used by the Los Angeles Police Department. It is a hip-length, lightweight jacket with a permanent lining. That lining was removed and replaced with an integrated Kevlar lining that increased total jacket weight slightly. Comfort and appearance of the modified jacket were judged acceptable.

3. Civilian garments. Civilian garments initially selected for fabrication with protective materials included sport coat, dress vest, raincoat and golf jacket designs.

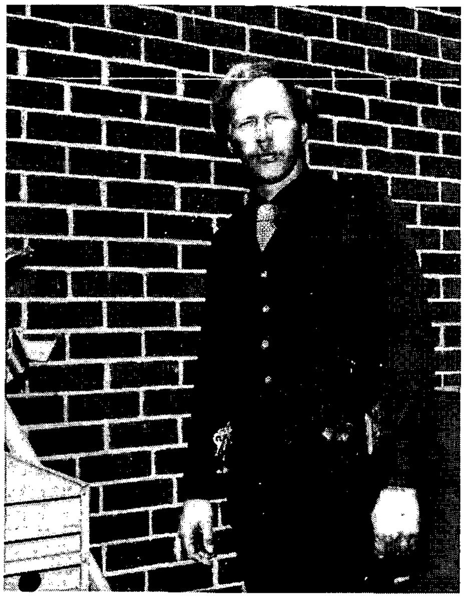
The Aerospace Corporation effort was focused on sport coat and dress vest designs, and six different models were developed in each category. These garments are discussed in the paragraphs that follow.

a. Sport coat, Figure 27(a). Fabrication of these garments with an integral Kevlar lining/filler was an iterative process, and each successive design was an improvement over the previous design. Both wool and heavy weight gabardine were successfully used as the outer material. In order to achieve satisfactory appearance, drape, and comfort, it was necessary to end four plies of Kevlar at the waist and continue with the remaining three plies below the waist. In addition, the protective material around the sleeve attachment and at the shoulder was cut back to reduce discomfort introduced by the stiff Kevlar.

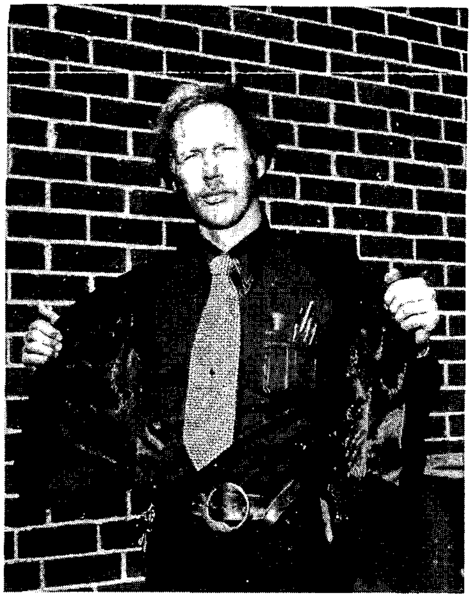
Although the final design resulted in an attractive and functionally acceptable sport coat, there was some concern expressed over the adequacy of the frontal protection offered by this category of protective garment. When a plain clothes officer wearing this garment reaches for his weapon, he must open the coat, which leaves the front of his body unprotected. A protective dickey or dress style vest would probably be used with the sport coat to provide the desired frontal protection. Public figures are, of course, not faced with the gun access problem.

b. Dress vest, Figures 27(b) and (c). The dress-style vest developed under this program was the more acceptable protective garment for civilian applications. It was relatively simple to manufacture and could be

(a) Sport Coat



(b) Dress Vest, Buttoned



(c) Dress Vest, Unfastened

Figure 27. Prototype Civilian Protective Garments

made in a variety of styles, outer materials, and patterns. Moreover, a dress vest represents a practical garment that can be worn in combination with most styles of clothing. The comfort and appearance of Kevlar-lined vests were considered acceptable.

4. Conclusions. Based upon the knowledge and experience acquired in developing prototype 7-ply Kevlar protective garments, it was concluded that useful garments can be provided for both law enforcement and civilian applications. Except for a weight increase of approximately 26 ounces over the weight of the same garment without Kevlar protection, soft upper torso protective garments with acceptable wearer comfort and satisfactory appearance are feasible.

Undergarments, civilian sport coats and dress vests, as well as a large variety of police uniform coat and jacket designs, can all be converted into protective garments. It became quickly apparent, however, that protective garments using Kevlar material for ballistic protection should be initially designed and fabricated with the Kevlar liner/filler. Modifying or retrofitting existing commercially available garments to accept a Kevlar liner/filler is a more difficult and costly procedure.

CHAPTER V. PRELIMINARY WEARABILITY TESTS

The final phase of the FY 74 Protective Armor Development Program involved preliminary wearability testing of soft protective armor garments developed during the prior program phases. The objective of this final phase was to evaluate the comfort, utility, wearability, and appearance of Kelvar-29 garments in an operational field environment and to guide the establishment of garment requirements, specifications, and designs for the follow-on field test program planned for FY 75. The total effort included consultation with law enforcement agencies concerning their interest in participating in the program, selection of four field test sites, design and procurement of 73 test garments representing 11 different garment types, coordinating the field testing activities, and collecting and evaluating the test results of these pilot field tests.

More detailed discussions of the activities involved in this final phase of the FY 73-74 program are given in the subsections that follow.

A. Test Objectives

The overall objectives of the preliminary wearability tests included:

- An evaluation of the appearance, acceptability, and inconspicuousness of Kevlar-29 protective garments relative to conventional uniforms and garments.
- An evaluation of the utility and wearability of Kevlar-29 protective garments by law enforcement personnel during the performance of their duties.

- An assessment of wearer comfort under a variety of ambient environments and climatic conditions for a spectrum of Kevlar-29 protective garments.
- Reactions on the general acceptability (or nonacceptability) of the concept of soft body armor by various elements of law enforcement agencies.
- An evaluation of the degradation (if any) in the protection provided by the test garments due to short-term exposure to operational field environments.
- The development of user guidelines and training aids on the wear and care of Kelvar-29 protective garments.

B. Participants and Functions

Although guidance and support was obtained from interested law enforcement agencies, the final responsibility for overall planning and implementation of the preliminary wearability tests was placed with The Aerospace Corporation. The scope of The Aerospace Corporation activity included identification of the garment types to be tested, preparation of design and procurement specifications, and subcontracting test garments procurement from selected suppliers, preferably with both uniform and armor experience. Aerospace also prepared and provided record keeping and data forms to all test participants and also engaged in pre-test, in-process, and post-testing reviews with selected wearability test participants. Completed data forms were collected during and upon completion of testing, and analysis and evaluation of this collected information were performed. The results thus obtained and the conclusions reached were supplied to and coordinated with the test participants.

Selection of the test participants was based on the desire to obtain broad coverage of climatic, geographic, and uniform styling conditions. Another constraint was, of course, the willingness of local law enforcement agencies to participate in the test program. Four cities satisfying these requirements were chosen as test sites. They were New York City; Columbus, Georgia; Jacksonville, Florida; and Inglewood, California.

New York City represents extremes in climatic conditions. Summers are hot and humid, and winters are normally cold and damp. Florida, on the other hand, has a relatively stable climatic situation. Temperature variations are small from summer to winter, and the relative humidity is consistently high. Garments worn by law enforcement officers throughout the entire year are relatively light weight.

The temperature extremes in Columbus, Georgia, are similar to northern Florida, but the general temperature level is somewhat cooler. Police uniforms are relatively light weight, but heavier jackets are needed at certain times of the year.

The seasonal temperature variation in Inglewood, California (located in the Los Angeles basin), is also not large. Summer temperatures reach the high 90°F's. However, these high temperatures are usually accompanied by low humidity, and diurnal variations of 30 to 50°F are not uncommon. Low winter temperatures are in the 40 to 60°F temperature range.

Members of the law enforcement agency in each participating test area assisted in planning the details of the test program to be conducted by their agency. Their functions and responsibilities included guiding the selection of garment types, assignment of garments to test participants, monitoring garment use, dispensing and collecting data collection forms, identification and classification of unusual incidents, garment maintenance, and review of program progress and findings.

The interrelation of The Aerospace Corporation responsibilities and the functions provided by the law enforcement agencies in the participating cities is shown diagramatically in Figure 28.

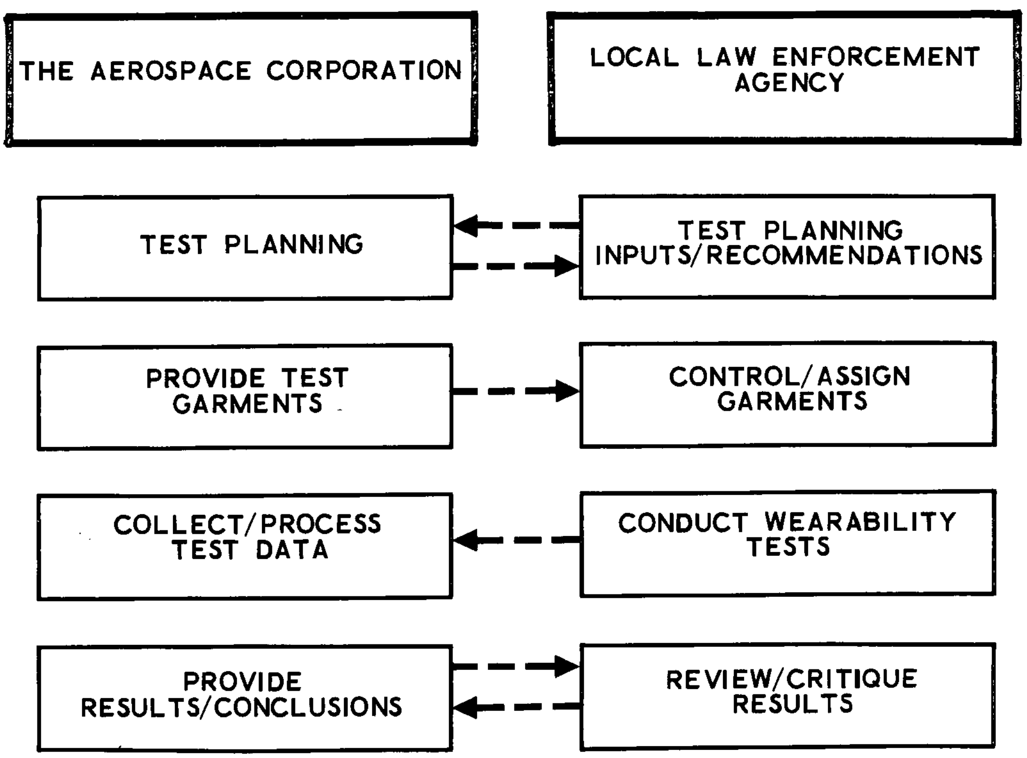


Figure 28. Interaction Between Wearability and Test Functions

C. Garment Types

Two general types of protective garments were used in the wearability tests. One was a special accessory type of garment of which undergarments and body shirts are representative. The other type was an "integrated" garment in which the protective material is incorporated into a standard outerwear garment such as a sport coat or a uniform coat or jacket. In the latter case, the protective Kevlar was provided either as a detachable lining or as a permanent lining. With both the detachable and integral lining designs, care was taken that the outward appearance of the garment did not change.

A total of 73 protective garments, representing 11 different garment types, were procured for these tests. The garment types selected for testing were representative of garments normally worn by the police in each test city. The specific number and type of protective garments provided each test site are listed in Table 14. Within the limitation of the small number of garments involved in these tests, the attempt was made to assess a representative sample of garment types. In addition, emphasis was placed on garment types that are routinely worn in order to obtain maximum wear and exposure during the testing period.

D. Test and Evaluation Procedure

The wearability test program was conducted in general accordance with a previously prepared test and evaluation plan. That plan is included as Appendix E of Volume III of this report. The tests were designed to obtain data on garment comfort and garment wear characteristics under operational

Table 14. Test Garment Distribution

New York City		Jacksonville, Florida		Inglewood, California		Columbus, Georgia	
No.	Type	No.	Type	No.	Type	No.	Type
1	Reefer coat	6	Sport coats	4	Vinyl jackets	5	Undergarments (original)
1	Summer blouse	6	Dress vests	1	Leather jacket	2	Undergarments (redesigned)
2	Leather jackets	4	Under-garments	4	Under-garments		
6	Scooter coats	4	Short vests	3	Short vests		
5	Under-garments	2	Body shirts	2	Body shirts		
4	Short vests	3	Long vests	3	Long vests		
2	Body shirts						
3	Long vests						

conditions. However, since testing occurred during the summer of 1974, most of the information obtained was for summer-weight garments, and only limited information was collected at that time for the heavier, winter-type garments.

Garment evaluation was based upon information provided by the test participants. Both direct interviews and questionnaires filled out by garment users were utilized. (Copies of some of the questionnaires are included in Volume III, Appendix E.) In addition, reviews were held with participating agencies at selected times during the test period.

The assessment of garment comfort was subjective and was based on coolness and general feel when worn as well as any hindrance or restraint in movement both in normal wear and during typical operational situations such as interviews, interrogations, traffic violations, arrests, pursuits, stake outs, etc. In addition, comparisons with existing and available soft armor (generally 4-pound ballistic nylon pads, front and back) were solicited. Such information was combined with user-suggested physiological design changes to aid in guiding garment redesign and in selecting garment types for subsequent field testing. Garment wear assessment was made both during and at the conclusion of the testing period by visual inspection.

During the duration of the test, control and maintenance of the garments were the responsibility of the testing agency. When the test program was completed, all garments were returned to The Aerospace Corporation for post-test inspection and evaluation.

1. New York City. Twenty-one officers participated in the test and six different types of garments were actually worn: two long undergarments (body shirts), five shorter undergarments, three long vests, four short vests, two leather jackets, and one summer blouse. Of the 21 officers, two were horse patrolmen, three were assigned to auto patrol, nine to the tactical squad, five to the emergency squad, and two were detectives with the emergency squad. One of the participating officers was a sergeant. The test

was begun during April 1974 and was completed in August 1974. Each officer filled out an interview questionnaire before wearing the garment. During the period he wore the garment, the officer filled out weekly data forms and, when he returned the garment, filled out a post-test questionnaire. During the test there were six incidents that were reported, and the incident questionnaire was filled out each time. At the conclusion of the test, five of the officers were interviewed by phone.

2. Jacksonville, Florida. Twenty-five officers participated in the test and six different types of garments were actually worn: two long undergarments, three shorter undergarments, two long vests, three outer vests, three sports jackets, and five dress vests. Of the 25 officers, 16 were on auto patrol, one was on motorcycle patrol, and eight were detectives. The test was begun in May 1974 and concluded in September 1974. The officers filled out the same data forms as the New York police, and during the test there were two incidents reported on incident forms. At the end of the test, phone interviews with selected officers were conducted.

3. Columbus, Georgia. Five early prototype undershirts were supplied to Columbus in February 1974 for wearer reaction and redesign suggestions. Feedback was limited to verbal interviews, and the garments were returned after a brief wearability field test. After redesign, two improved undershirt garments were supplied in August 1974 to a robbery stake-out unit. A sergeant and two of his men have worn the garments. They have supplied interview comments, and have completed and returned form questionnaires.

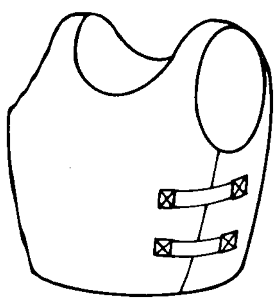
4. Inglewood, California. Eight officers, all on auto patrol, participated in tests on four different garment types. The garments actually worn included two long undergarments (body shirts), four undershirts, one outer vest, and one vinyl jacket. Results were obtained by in-person interviews as well as questionnaires completed by the participating officers, all of whom displayed enthusiasm for the soft body armor concept.

E. Summary of Test Results

The wearability tests were conducted between April and October 1974. The weather at the test sites was generally hot and, with the exception of Inglewood, also humid. As a result, some of the garments, such as those designed for winter wear, could not be worn on duty and only a limited comfort assessment could be provided. Nevertheless, a sufficient sampling of garment styles was worn, and a determination of wearer acceptance and user problems could be made. Wearer information was submitted weekly on supplied data forms and computer compiled. Upon completion of the test period for a specific garment, wearer interviews were also undertaken. A summary of each interview is included in Appendix D of this volume. The information and results given in Figure 29 for an undergarment are typical of the type of information acquired.

1. Garment comfort. There was one common problem with all of the garments worn during the tests, namely heat containment. The problem was sufficiently severe that in New York City during June, July, and August the garments could not be worn for a full tour of duty on an average day. This was also the case in Jacksonville. The problem persisted even at night.

- GARMENT TYPE: UNDERSHIRT, SIDE PROTECTION
- LOCATION: NEW YORK CITY - SPECIAL FORCES
- WEAR PERIOD: APRIL TO AUGUST 1974
- EXPERIENCE: 7 OFFICERS WITH 42 WEEKLY REPORTS
- SHIFT: 37% AM 4% PM 55% BOTH 4% OTHER
- ASSIGNMENTS: 74% AUTO PATROL 20% FOOT PATROL 6% OTHER
- WEAR HISTORY: 70% FULL TIME 20% HALF TIME 10% VERY LITTLE
- DISCOMFORT: 74% HOT 20% RIDES UP



QUALITATIVE WEAR SUMMARY (Percent)

	AGREE	NEUTRAL	DISAGREE
EASY ON/OFF	95	1	4
FITS WELL	80	10	9
FREE MOVEMENT	98	-	-
EASY WEAPON ACCESS	100	-	-
NORMAL MANEUVERABILITY	98	2	-
NO CHANGE IN COMFORT	32	16	35

Figure 29. Typical Wearability Test Results

In Inglewood, the officers complained about heat discomfort but wore the garments. It would thus appear that high ambient humidity contributes markedly to the problem. In any case, it is clear that the garment must be designed to allow greater air circulation between the garment and the body of the wearer or with larger cutout areas for additional body heat rejection.

2. Garment fit. Another problem that bothered most of the wearers was poor garment fit, usually caused because the garment had not been sized for the specific individual wearer and the adjustment range was limited. A number of participants suggested that custom-tailored garments should be considered.

3. Style preference. For uniformed patrolmen, the undershirt was the most acceptable protective garment style. They want a garment that can be inconspicuously worn at all times. Both long and short vests were considered less desirable as full-time wear garments as they could be seen and recognized when worn and could result in the head becoming the target. Also, if such garments are not worn at all times, there may not be sufficient time to don the garment in some instances. Most of the officers quickly adjusted to wearing the undershirt and reported that it did not hinder their movements or access to their weapon. In the stress situation of subduing a suspect, no interference with the officer's activity was encountered. However, two shortcomings in the undershirt design (in addition to comfort and fit) were encountered. When the officer sat in the patrol car, the ballistic material rode up on the body to under the wearer's chin. Also, the outside shell cover over the ballistic material bunched up and created discomfort.

The sport coats were not well accepted by the three Jacksonville detectives who wore them. All three felt they were too hot, and two reported they were heavy and cumbersome. One officer reported that the coats always appeared rumpled as if in need of pressing. This same officer observed that although such a coat might be satisfactory for unarmed public officials, he had to open the entire front of the coat when going for his weapon, thus defeating the purpose of wearing such a garment.

The dress vests worn in Jacksonville were considered more acceptable for plainclothes wear than the dress sport coat. The vests were considered inconspicuous and acceptably comfortable as they could be unbuttoned and loosened. This type of vest was also preferred over the long and short outer vests that are obviously recognized as protecting garments when worn. Nevertheless, some interest was also expressed in these outer vest designs as well.

The vinyl and leather jackets and even the NYC summer blouse proved to be too hot towear during the testing period. As a result, the wear-ability tests on these garments were incomplete at the time of publication of this report.

F. Garment Redesign

The knowledge and experience acquired during the preliminary wear-ability tests influenced plans for the garment field tests scheduled for FY 1975. In some cases, little interest was shown by the potential users toward some of the garment styles, and as a result, such garments are receiving little consideration for full-scale field testing. In other cases, interest in the garment type was high, but improvement in comfort and fit was needed. For these cases, garment redesign has been undertaken and the improved garments are to be used in the planned field tests.

The undershirt is an example of a garment in this latter category. It was generally accepted as a preferred protective garment style, but numerous suggestions to improve the design were offered. In response to these comments, the armholes have been enlarged to improve ventilation and to reduce chafing. A new undergarment has also been designed with shaped front and back panels, and open spaces between the panels. This design is intended for use under hot and humid conditions but at the expense of some side protection. Also, in order to make the undershirt designs more comfortable and simultaneously ensure a better fit, greater adjustment is being provided.

Similarly appropriate design modifications will also be incorporated in the other protective garment styles that are being considered for field testing.

CHAPTER VI. PLANNED FIELD EVALUATION

As previously indicated, current plans call for the initiation of a comprehensive protective garment field test program during CY 1975. The objectives of the field evaluation include:

- A comprehensive assessment of user acceptance of a continuous-wear, limited-protection, protective garment.
- Acquisition of data and experience on the long-term wear characteristics of Kevlar-based protective garments.
- Acquisition of a sizeable data sample on test garment performance.
- Acquisition of information on cost-effective fabrication of protective garments.

At present, 15 cities are being considered as possible participants in the field evaluation program. It is anticipated that as many as 4000 garments may be required. Procurement action is already underway for 15,000 yards of Kevlar cloth, 3000 undershirts (see Appendix C of Volume III of this report), and a variety of other police uniform components and special purpose garments.

In addition to the garment design change suggestions (discussed in Section V.F), the experience acquired during the preliminary wearability tests also resulted in the incorporation of the following features in the field evaluation program:

- <u>Special Coordinator at Each Participating Agency</u>

  Cooperation at all levels of a participating police department is essential for a successful field test. In addition, an on-site coordinator (preferably a member of the department) is also necessary. The function of the coordinator is to ensure garment wear by the participating officers as well as the timely submittal of all desired data forms and questionnaires. In addition, the coordinator will supply liaison between The Aerospace Corporation field test program manager and the test site.

- <u>Individual Fitting of Test Garments</u>

  An improperly fitting protective garment virtually guarantees negative comments and discourages participant wear. Where feasible, garments are being designed with some adjustment capability. In the practical sense, however, all adjustments are limited. Consequently, real attempt must be made to distribute garments that are initially properly matched to the wearer and require only small adjustment.

- <u>Demonstration of Protective Garment Capability</u>

  The most effective means for acquiring the confidence of participating personnel is to demonstrate the ballistic-resistance capability of the protective garments being field tested. An actual firing at a garment should be performed for all test participants. The flexibility of the garment and the minimal constraint imposed on the wearer should also be demonstrated. If live demonstrations prove to be impractical, a film demonstration should be provided.

- <u>Wearer Orientation Sessions</u>

  In order to facilitate the test program execution and maximize the effectiveness of the information obtained, it is necessary to maintain a well-informed group of participants. Detailed discussions on the purpose of the program should be held with all garment wearers. Specific guidance on how to complete the weekly data forms and questionnaires should be provided. Instructions on the care of the garments (washing, cleaning, precautions, etc.) should also be given.

A field evaluation test plan is being prepared and will be published separately prior to the initiation of the field tests. The plan will be individually coordinated with the 15 participating agencies. The document will also include the test objectives, assignment of responsibilities, evaluations desired, and type of information to be acquired.

APPENDICES

APPENDIX A. INDUSTRY/USER SEMINAR

As part of the LEAA plan to transfer government-developed technology to both the industry and user, a seminar on body armor was held at the Hilton Hotel in Washington, D.C., from 23 to 25 September 1974 in conjunction with the International Association of Chiefs of Police Conference. Six identical presentations, two each day, were prepared and presented by The Aerospace Corporation.

The presentations covered the knowledge and experience acquired during FY 73 and FY 74 on the soft body armor program funded by LEAA and represented a summary overview of the material included in this report. The structure and content of each presentation were as follows:

• Introduction	Purpose of presentation, LEAA role
• Program Goals	Key objectives, problem statement, issues
• Operational Requirements	Assault data, threat survey
• Technical Evaluations	Materials, phenomenology, blunt trauma loading
• Prototype Garments	Garment design, test results
• Field Evaluation Planning	Test objectives
• Future Efforts	Further investigation, test standards

A

In addition to the formal briefing and film presentations, a variety of protective garments developed under the LEAA-supported program were displayed (Figure A-1). Various garment types, such as uniform components, civilian garments, and special accessory garments, were included in the display. Samples of different types of Kevlar fabric and examples of clay backface signatures from ballistic tests of Kevlar fabric were also exhibited.

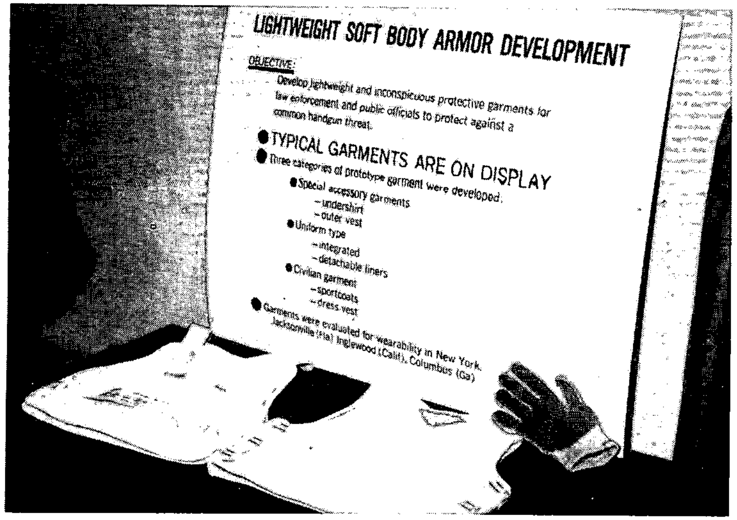
Each presentation was followed by questions and discussions from the floor, which generally focused upon the technical and legal aspects of body armor use. Some of the important subject areas of concern to the attendees included:

- Level of Protection Provided by LEAA Garments

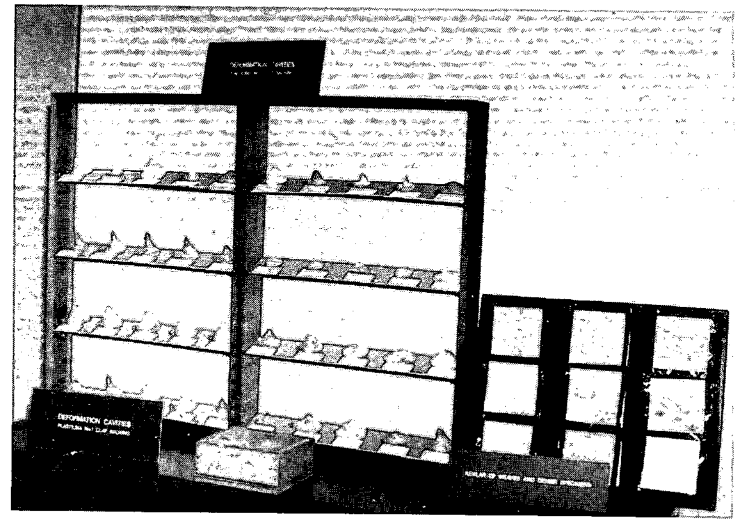
  The concern of many of the law enforcement officers and body armor manufacturers was that the level of protection for which the LEAA garments are designed is too low. Most commercial protective armors are advertised as capable of defeating a significantly higher-energy ballistic threat than the .38 caliber bullet at 800 feet per second. It was agreed that in most cases commercial garment types are rather conspicuous and not generally adaptable to routine wear. Also, little is known about their blunt trauma protection at these higher energy levels.

- Liability Considerations of Body Armor Suppliers

  Concern was expressed by many of the body armor suppliers as well as by the potential users and wearers of soft body armor



(a)



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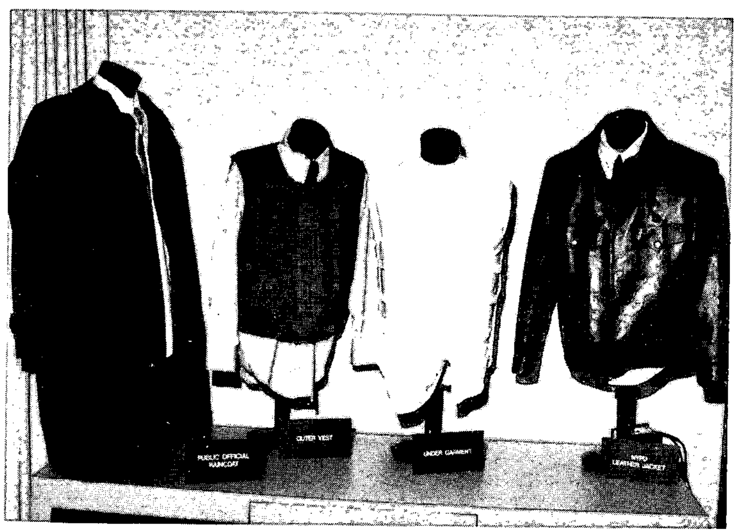


(c)

(d)

Figure A-1. Exhibits at Industry/User Body Armor Seminar over liability considerations in a shooting incident. The question was asked, "Who is liable and to what degree for the advertised protective capability of body armor?" No conclusion was reached on the issue except to observe that each incident would have to be examined and resolved separately. It was agreed that an appropriate disclosure statement must accompany each individual protective garment.

- Maximum Level of Acceptable Blunt Trauma

  The goal of body armor manufacturers is to design and fabricate lightweight protective garments that not only protect against high energy ballistic threats but also minimize the degree of blunt trauma damage to the wearer. Various attendees expressed concern that a maximum acceptable degree of blunt trauma to the wearer still needs to be quantitatively established.

- Acceptance Test Standard for Body Armor

  Many of the manufacturers voiced a need for a uniform acceptance-test standard for body armor. It was indicated that the National Bureau of Standards (NBS) will define this standard when needed data become available. Also, the NBS will recommend testing techniques for determining blunt trauma effects behind soft armor.

A total of 78 individuals, representing manufacturers, distributors, and users of body armor, attended the seminar. By affiliation, the attendees included:

13	Police chiefs or equivalent
2	Police commissioners
3	Law enforcement administration and training officers
7	Scientists involved in research and development phases of body armor
48	Manufacturers and distributors of commercial body armor and uniforms
4	Representatives of national associations pertaining to crime statistics and prevention
1	Newspaper reporter representing the Boston Globe

Each attendee was provided with an annotated data package containing copies of all charts presented at the seminar.[2] The general consensus among attendees (based upon written comments entered on the registration cards) was that the data and exhibits presented were extremely informative. Numerous attendees suggested that a second seminar be conducted at a later time, possibly at the conclusion of the field evaluation tests.

APPENDIX B. SUMMARY OF ASSAULTS ON OFFICERS WEARING BODY ARMOR

1. Introduction

Between the end of May and the middle of July 1974, three California police officers wearing currently available soft body armor were shot while in the process of questioning or apprehending suspects. In each case, the officer involved suffered only minor injury in a situation where death may have occurred without the protection of body armor.

In view of the importance of these cases in providing information for evaluation of lightweight body armor for law enforcement personnel, The Aerospace Corporation initiated an investigation of each of these incidents. These investigations included interviews with the officers who were shot, their superiors, and attending medical personnel, as well as a review of medical reports and other available data concerning the incident. Dr. John Benfield, Aerospace medical consultant, participated in two of the investigations. In addition, firing tests were performed on the types of armor used, and the ballistic loading condition experienced in each case was simulated. These tests were intended to form a basis for general evaluation and comparison with Kevlar armor and also to provide correlation with blunt trauma data on animals reported by the Edgewood Arsenal Biomedical Laboratory.[6]

2. Incident Description

The three shooting incidents are described in the following paragraphs and are summarized in Table B-1. All three incidents were generally

Table B-1. Summary of Officer Assault Incidents

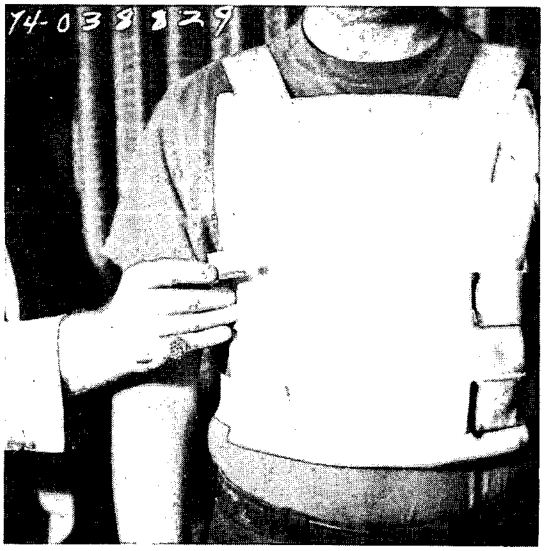
Incident	Approximate Weight (lb)	Protection	Weapon	Wound	Bullet Perturbation
Los Angeles (Officer F. G.)	195	Centurian Vest	.32 caliber Colt, automatic, 4-inch BBL	Small abrasion 3- to 4 inches in diameter; bruise on chest	Bent name tag
San Francisco (Patrolman B. H.)	180	Second Chance Vest	.38 caliber Special Cobra, 2-inch barrel 158 gr round nose	Small welt 3-inches in diameter; bruise on sternum	Heavy leather jacket, shirt, and tie
San Bernardino (Officer V. C.)	160	Second Chance Vest	.38 cal Smith and Wesson, 6-inch barrel; semi-jacketed, hollow point	Small abrasion 2-inches in diameter; bruise on chest	Grazed arm; sun glasses in pocket

similar. Each officer received only minor injuries that normally would not have required hospitalization. Photographs of the protective garment worn and the bruise resulting from the impact in the Los Angeles Police Department (LAPD) incident are shown in Figure B-1.

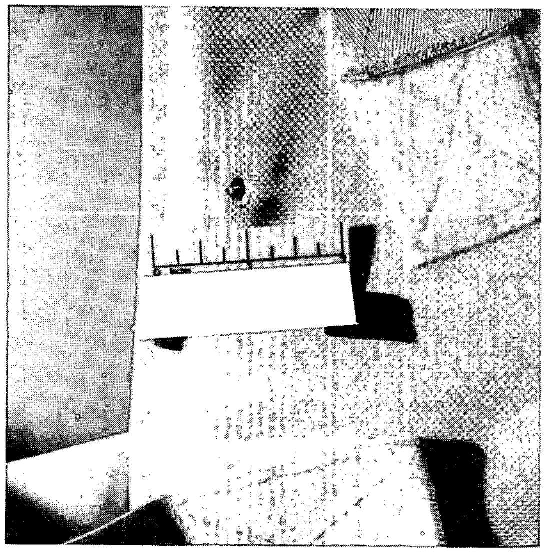
a. Officer F. G., LAPD Harbor Division

(1) Scenario. On 31 May 1974, the officer, on a motorcycle, observed a pickup truck make an illegal left turn. The officer made the stop, and as he approached the truck the driver stepped out of the vehicle, drew a weapon, and fired at the officer. The officer was struck on the right side of the chest, the bullet just nicking his name tag before encountering the armor. The officer withdrew and called for assistance. Three more shots were fired by the assailant and two by the officer, none of which resulted in injury to either party. The officer demanded the suspect give up and he was taken into custody. After the incident, the officer was transported to the Carson Inter-Community Hospital for observation and treatment.

(2) Protection. The officer was wearing a Centurian vest of ballistic nylon. This vest consists of two pads, each 12 × 14 inches, containing 18 plies of ballistic nylon and having a total weight of 4.5 pounds (areal density ~1.9 pounds per square foot). The vest is manufactured in the Los Angeles area.



(a) 18-Ply Nylon Vest Worn by Officer



(b) Close-Up of Bullet Imbedded in Vest

(c) Surface Laceration Caused by Bullet

Figure B-1. Results from a Specific Shooting Incident

(3) Threat. The weapon used by the suspect was a .32 caliber Colt automatic (S/N 250453). The ammunition used was Winchester-Western factory loads. The distance between the weapon and the officer was estimated to be approximately 20 inches at the time it was fired. It is of interest to note that the weapon apparently malfunctioned during the exchange of fire, as four live rounds were ejected on the ground. Later tests by the LAPD Scientific Investigation Division, revealed that the safety was loose and exhibited a tendency to jam the trigger.

(4) Armor interaction. The bullet struck the vest 4-3/4 inches from the top edge and 5/8 inch from the right edge. The bullet penetrated approximately 1/2 to 2/3 of the total material plies. The bullet was retained in the material and exhibited a slightly mushroom shape.

(5) Trauma effects. The resulting wound included a small abrasion and a resulting 3- to 4-inch diameter bruise on the right side of the chest. The medical assessment in the shooting report stated that the wound was a "2 cm. abrasion at the right anterior auxiliary, 1 inch above the right nipple."

(6) Officer perception. The officer described the impact of the bullet on the vest as being similar to that occurring if someone were to push his shoulder back. He was in full command of his senses at all times and immediately drew his weapon to defend himself.

(7) Garment history. The officer indicated that he had purchased the vest about one year ago for approximately $60 after the shooting death of another officer. He had been wearing the garment continuously since that time. He has never washed the garment but applies talcum powder.

(8) Action. The officer was interviewed by Aerospace personnel two days after the incident and again several weeks after the incident. A request was made for a complete copy of the LAPD firing report. It was indicated that this document would not be available until after disposition of the case.

b. Patrolman B. H., San Francisco Police Department

(1) Scenario. On June 14, 1974, the motorcycle patrolman was assaulted with a gun during a routine traffic stop of a vehicle for excessive noise. The officer was struck in the sternum and knocked down. After the incident he was examined by a staff physician and held in the hospital for one day for observation.

(2) Protection. The patrolman was wearing a two-pad (4-5-pound front and back) Second Chance vest with 18 layers of ballistic nylon in each 12 × 14-inch pad. This design is similar to the Centurion vest worn in the incident described in Section 2.a.

(3) Threat. The weapon used was a .38 caliber Cobra Special with a 2-inch barrel. Ammunition was determined to be a 158 grain,

round-nose bullet. The distance between the weapon and the patrolman was estimated to be approximately 4 feet at the time he was shot.

(4) Armor interaction. The armor exhibited an indentation opposite the sternum. The outer layer showed some stretching of the weave pattern, but no breakthrough. No damage occurred to the second layer. The patrolman was wearing a heavy leather motorcycle jacket, shirt and tie over the vest.

(5) Trauma effects. The patrolman sustained a small (dime size) welt on the sternum. A three-inch diameter bruise appeared several days later.

(6) Officer perception. The bullet impact produced a stunning effect similar to a jab from a stick. The attack came as a surprise and he never saw the gun. He believes he was stunned for less than a second.

(7) Garment history. The patrolman had worn the protective vest for over a year, primarily for skid protection on his motorcycle. He purchased the armor through another officer and paid approximately $60. The vest had been washed about four times.

(8) Action. The patrolman was interviewed by Aerospace personnel shortly after the incident. The patrolman's commanding officer was also contacted, and the crime laboratory report on an examination of the vest was obtained.

c. Officer V. C., San Bernardino Police Department

(1) Scenario. On 14 July 1974, Officer V. C. and two other officers responded to a routine complaint call involving a disturbance. The officers encountered three men who refused to identify themselves. The men started an altercation with the officers, which proceeded into the back yard of a home. One of the officers was beaten and his gun taken away by the assailants. An exchange of gunfire took place, and the officer was struck in the left breast and knocked down by the assailant using the first officer's weapon. The assailant was killed by Officer V. C. after he had been shot. The other two suspects were arrested and charged with attempted murder.

(2) Protection. The officer was wearing a Second Chance vest comprised of two 12 × 14 inch pads of 18-ply ballistic nylon. The weight of the vest was approximately 4.5 pounds.

(3) Threat. The officer was assaulted with a .38 caliber Smith and Wesson revolver having a 6-inch barrel. Distance between the weapon and the officer was estimated to be between 8 to 10 feet.

(4) Armor interaction. The armor was struck approximately 3 inches to the left of the centerline of the vest. The bullet was retained in the armor, but was oddly deformed. The bullet is believed to have grazed the officer's arm and then hit a pair of sun glasses in his breast pocket.

(5) Trauma effect. The bullet impact resulted in a 3/4-inch abrasion 3 inches left of the centerline of the chest and approximately

4 inches below the left breast. A 2-inch diameter bruise appeared 4 days later.

(6) Officer perception. The officer was knocked down by the impact, but he reported no sensation of pain or coughing of blood. He was able to get up and function immediately.

(7) Garment history. The officer's partner encouraged him to buy the armor initially. It also cost $60. He wears a tee shirt under the armor and has not subjected it to laundering except around the neck. He reports no discomfort problems in wearing the vest, and feels that it does not hinder his mobility.

(8) Action. The officer, his commanding officer, and his doctor were interviewed by Aerospace personnel and medical consultant, Dr. John Benfield, 4 days after the incident. A formal request was made for wound, vest, and bullet photographs as well as pertinent medical records.

3. Clay Cavity Correlation

The ballistic loading conditions for the incidents described in Section 2 were duplicated at the Sierra Engineering firing range. The same type of protective garment worn by each officer was subjected to the threat actually encountered. To provide a permanent backface signature record, clay backing was used. Similar clay cavity data were also obtained for the same threat with 7-ply 400/2 (36 × 36) Kevlar. A summary of the results observed is given in Table B-2.

Table B-2. Ballistic Test Clay Cavity Measurements

Vest	Weapon (caliber)	Velocity (fps)	Cavity: Equivalent Diameter (inch)	Cavity: Depth (inch)	Comment
Second Chance	.38	856	2.78	.87	Officer B.H. case
Second Chance	.38 (Super Vel)	1022	2.84	.77	Officer V.C. case
Second Chance	.357	1128	2.89	1.48	
Centurian	.32	864	1.81	.69	
Centurian	.32	848	1.99[a]	.94[a]	Officer F.G. case
400/2 (7 plies)	.38	874	2.24	1.73	
400/2 (7 plies)	.32	872	1.69	1.19	
400/2 (5 plies)	.38	864	2.38	1.89	

[a]Larger cavity than normal due to close proximity to edge of armor.

As expected, the heavier and thicker 18-ply nylon protection of the commercially available protective vests produced a larger diameter, but smaller depth, cavity than resulted for the same threat with the lighter and thinner 7-ply Kevlar. As discussed in Section 2, the blunt trauma resulting from the incidents described was negligible. Thus, the cavities produced by the corresponding threats may be considered a measure of acceptable backface signatures. Similarly, the backface signature for 7-ply Kevlar, although more area-concentrated and deeper, is also considered acceptable from a blunt trauma viewpoint (see Reference 6). On the basis of such information, a preliminary blunt trauma correlation is now available with clay-backed ballistic tests. Obviously, caution is necessary in drawing quantitative comparisons since there was some bullet interaction with other material in addition to the protective vest (bent name tag, leather jacket, sunglasses). Moreover, in the case described in Appendix B, Section 2.a, the bullet struck very close to the edge of the vest.

4. Summary

- In all three incidents, the officers were saved from serious injury that might have been fatal by wearing a commercially available, nylon, protective vest. Only a surface bruise and no measurable internal damage resulted.
- The heavier, commercially available, nylon vests have a density of approximately 1.9 pounds per square foot of protective area and yield a smaller backface clay cavity in

ballistic tests than does 7-ply Kevlar (approximately 0.4 pounds per square foot).

- Based upon ballistic tests with 7-ply 400/2 denier Kevlar, it was concluded that serious injury would also have been prevented had the officers been protected by 7-ply Kevlar vests. The bruises would have been more severe but the extent of blunt trauma is uncertain.

APPENDIX C. OTHER KEVLAR PROTECTIVE APPLICATIONS

The high strength characteristics of Kevlar that make it attractive as a protective garment material against ballistic threats has led to its consideration as a protective material for other applications as well. A short discussion of some of the other protective uses for which Kevlar is being considered is given in the succeeding paragraphs.

1. Shark Attack Protection

Work by scuba-equipped personnel on certain important U. S. Navy projects is often suspended when a shark attack hazard exists. If these personnel could be provided with appropriate protection against shark attack, work interruption could be avoided.

The demonstrated ballistic qualities of Kevlar fabric suggested a potential use for shark attack protection as well. To assess the feasibility of this latter application, a lead-weighted spool was covered with a layer of wetsuit material, which was then enclosed in seven layers of Kevlar. Mylar film was inserted between the individual layers of Kevlar to establish the puncture depth of any shark bites.

The test assembly was saturated with fish meal and towed alongside a Navy research ship. Numerous sharks approximately 6 to 7 feet long were attracted to the vessel, and the test assembly was repeatedly attacked and bitten. Subsequent examination revealed that no penetration of the wetsuit material had occurred and that only four of the seven layers of 400/2 denier

Kevlar had been penetrated. It was concluded that no puncture or gash injury would have been sustained by a diver protected by a 7-ply Kevlar outer garment.

As a result of this preliminary test, the U. S. Navy has undertaken a more extensive assessment of Kevlar material for this application.

2. Dog Handler Protection

A preliminary investigation was conducted with the cooperation of the Dog Training Section of the Richmond, Virginia, Police Department to evaluate the use of Kevlar as a protective material for guard dog training. Eight layers of Kevlar fabric (400/2 denier) were wrapped around a trainer's forearm and then covered by a jacket sleeve. There was no penetration through the Kevlar even after repeated attacks by the dogs, nor was there any injury to the trainer's arm.

The dog trainer who participated in the test, recommended future use of Kevlar for this application. He considered Kevlar a more realistic training tool, as the use of bulky training protectors normally employed is avoided, and realistic clothing and a more normally-sized target can be used.

3. Other Ballistic Protection

A number of lightweight helmet designs for ballistic protection of law enforcement personnel are being developed and tested by several agencies. One such design incorporates a polycarbonate outer shell and multiple layers of Kevlar liner. A .38 caliber bullet fired at close range was defeated by this design.

At Edgewood Arsenal, ballistic tests have been performed on another type of lightweight protective helmet fabricated of Kevlar and a resin binder. This design defeated multiple hits by .38 and .22 caliber bullets fired at close range.

Kevlar-based hard laminates are also being considered as protective panels for law enforcement vehicles such as helicopters and automobiles.

APPENDIX D. PRELIMINARY WEARABILITY TEST INTERVIEWS

The preliminary wearability tests involved a number of different garment types and, in some cases, even several designs of the same garment type. Although much of the information assembled on wearer experience and reaction to the prototype garments used in the preliminary wearability tests was based on data forms and questionnaires completed by the participants, personal interviews were also conducted with a selected sample of participating officers. Each participant was requested to provide constructive criticism, and the information acquired proved to be of great value by providing additional insight on desirable changes in garment concepts and design. A brief summary of each interview is presented in the paragraphs that follow.

1. Undershirt

a. New York City Police Department

(1) Patrolman. Heat was a real problem. The garment was comfortable early in the morning, but it started to heat up by 10:00 a.m., and he usually had to remove it by 11:00 a.m. This meant going off duty for a period of time. The patrolman said it was especially bad in the direct sunlight or on humid days. Otherwise, the garment allowed satisfactory mobility, was not cumbersome, and did not hinder him in any way. The fit was not too bad. In general, he is in favor of the idea of lightweight protective garments, but the heat problem must be corrected. He pointed out that the crime rate is usually the highest in summer and that is when protective vests are most needed.

(2) Patrolman. Two officers rode together during the test, so only one officer reported the findings. He said their opinions were the same. He thinks the garment is "beautiful," but too hot for summer. He thinks it would be perfect for use during spring, winter, and fall. The patrolman said it feels like wearing a corset and slightly restricts his mobility, but that is not a real problem. He thought the lining material should be improved in order to prevent creeping up on the wearer. Although he thought the snaps were too small and perhaps fragile, none of them ever broke. In the direct sunlight the garment becomes an oven. It is also unbearable on hot days in the summer. Both officers often had to take their protective garments off in the middle of a tour because of the heat problem. When wearing the garment he felt more confident and secure; however, he did not take more chances. He said he would like to have the garment returned to him for full-time use.

b. Inglewood, California, Police Department

(1) Detective. This officer wore the garment during a 2-week test period, and at the time of the interview, he still had the garment and used it on hazardous duty. Although the garment is too small for him and does not completely cover his stomach, he likes the style. Before the test period, he wore a Second Chance, commercially available vest for 8 months. He was bothered that the Second Chance garment can stop higher powered bullets than can the test garment. He considers protection the major consideration in the purchase of a vest. He stated that the test garment took longer to get used to than did the Second Chance vest. He did adjust to the additional heat of the

test garment and also mentioned that the garment slightly restricts his movement (turning) and his access to his weapon. He stated that the snaps (fasteners) are becoming twisted and out of place. In general, he likes the garment but wants more protection than it offers.

(2) Patrolman. This officer has worn the garment on and off for approximately 2 weeks. In general, the garment was too hot and did not fit well. Also, it tended to bunch up at the bottom while sitting, giving a bulky feeling. He did not feel that his normal movement was restricted by the garment, although he feels it might be somewhat restrictive if he had to climb fences in pursuit, etc. He has relatively low confidence in the armor because it feels too thin. It should be designed to stop more than .38 caliber. He has owned Centurian armor for about 2 months, which he wears on occasion. He has more confidence in it, and it is not as hot. He wears the front panel only and sees no need for a back panel, as most encounters are frontal. He does not feel that he needs side protection.

(3) Patrolman. This officer put the test garment on only once for 20 minutes and decided not to wear it because it is too cumbersome, too hot, and rides up. He owns a Second Chance vest but does not wear it either because it too is hot and rides up. He wants a garment that is more flexible.

(4) Patrolman. The test garment was worn only sporadically during the test period because the officer was on vacation part of the time. He says he had difficulty putting the garment on. It was very, very hot. Instead of a plastic lining on the inside, he would rather have a nylon mesh

to make garment cooler. He says that once the garment is on it moves with you. His garment is too small, it does not cover all of his stomach. He likes the garment idea and would like it to become part of the standard uniform. He also said he would be willing to try an improved version.

c. Columbus, Georgia, Police Department

(1) Sergeant. The big problem with the garment is that it is too hot in the summertime. He could only wear it while on duty at night even though he was in an air conditioned patrol car. Usually he would wear it for 3 hours then had to take it off. Later he would put it on again for the last hour of his tour. He works on a unit that breaks up armed robberies. Once he fought with it on and had no maneuverability problem. He also did some running while wearing the garment. The only time he notices it is while sitting in the patrol car because it rides up. The other minor problem is that the snaps come undone. He said he feels more confident with it on, and his wife is greatly relieved to know he is wearing it. One of his men uses a shoulder holster and the garment makes this awkward. In summary, he likes the garment but it is too hot for the summer and rides up.

(2) Patrolman. He has only had the garment for 2 weeks and has not really formed any final opinions of the garment as yet. The garment is a little too big, and when worn in the patrol car, it "bunches up at the top." Another minor problem is that the velcro at the bottom is not holding; however, the straps on the chest are holding well. He works on a night shift, and on warm nights, the garment is too hot to wear. He has not had the garment

long enough to say whether he has confidence in it or even if he is glad to be wearing it. He did say the maneuverability with it on was good and that there were no hindrances.

(3) Patrolman. The garment is hot early in the evening but is not uncomfortable later on. He had two minor problems: (1) The snaps came loose, which cause the garment to fall off his shoulders and bunch up, and (2) the tail should be longer to prevent ride-up on the body. Also the garment is uncomfortable with a shoulder holster. He has not worn a Second Chance or any other armor. He is in a unit that has hazardous duty, and if the heat problem and the minor problems he mentioned were corrected, he would wear the garment all the time. He definitely likes the garment concept.

2. Bodyshirt

a. New York City Police Department

(1) Patrolman. Although he had some problems, he was very much in favor of the garment. The garment would not fit under his tailor-made uniform, and it actually ripped two of his uniforms. Also, it was impossible to wear in the summer due to the heat. However, when the temperature was in the 40's and 50's, it was fine. In order to demonstrate its flexibility, he wrestled a fellow officer while wearing it and was not hindered. His fellow officers were very skeptical about the garment until he shot it with his own revolver. When the bullet failed to penetrate the Kevlar, the fellow officers were extremely impressed. He does not think the garment is necessary for horse patrol officers as they are not usually involved with felonies. However,

he did feel an extra confidence and personal security while wearing the garment. He also thought the garment was well designed. He thinks it would be ideal for regular auto patrol officers.

b. Inglewood, California, Police Department

(1) Patrolman. The officer who was assigned this garment spent 2 days a week on the desk and 3 days in a patrol car. He liked the garment, although it was slightly large for him. He stopped wearing it because his uniform was not big enough to wear the garment underneath it comfortably. He noticed the extra heat due to garment, but felt it was something that one could live with and not a real problem. He noticed a seam was tearing on his garment. Access to his weapon did not present a problem. He liked the garment and had previously never worn a Second Chance or any other type of soft armor.

c. Jacksonville, Florida, Police Department

(1) Patrolman. The officer stated that the fit of the garment was generally comfortable. It did ride up a little and readjustment was needed about once per shift. The garment was, however, too hot for daytime wear, especially if frequent egress from the patrol car is involved. If the car interior was kept cool, wearer cool-down upon reentering the car seemed more rapid than when the garment was not worn. The officer was aware of commercially available protective vests but did not own one. He worked varied shifts and usually wore the garment on late afternoon and night assignments. The officer stated that he felt more confident while wearing the garment and liked the side protection it provided. If not for the heat problem,

he would wear the garment continuously. He suggested that the side straps should be widened to hold better. On the whole, he considered it an excellent garment.

3. Short Outer Vest - Inglewood, California, Police Department

a. Patrolman. This officer did not like the concept of an outer vest protective garment for continuous wear because it is clearly visible and readily recognized. In his opinion its use is most appropriate in hazardous situations that can be anticipated in advance. He also stated that such a garment should be capable of "stopping everything." On patrol, he would prefer to have an undershirt-type garment that he would wear all the time, if one were issued to him. He stated that the vest is well designed, very comfortable, and fits him well, but he wished its bullet-stopping capability were greater.

4. Long Outer Vest - Jacksonville, Florida, Police Department

a. Patrolman. The officer had three primary objections to the garment. First, it was too hot. He works the swing shift and found it was too hot at night as well as during the day. His maximum wearing time was 1.5 hours. After that, he had to take it off. His second objection was that it did not have enough stopping power. He owned a Second Chance vest, but his wife ruined it by washing it. He believes Second Chance has a higher stopping power. He reported that most of his fellow officers did not like the wearability test garments because of their low stopping power (as compared with commercially available protective garments). He considered this a very important objection. His third major objection was that the vest was worn on the outside. He would prefer to have an undergarment, so that criminals cannot see it. He commented that the garment did ride up and was cumbersome to wear in the patrol car, but that access to his gun was acceptable. In summary, he stated that the vest is useless to him as it is now designed.

5. Vinyl Jacket - Inglewood, California, Police Department

a. Patrolman. Officer reported that he wore the garment only on cool nights. He considered it similar to the fire retardant jacket issued by the Los Angeles Police Department that some Inglewood officers have. He stated that he would buy such a garment only if he felt he needed it. His preference would be a vest that stops everything.

6. Sport Coat - Jacksonville, Florida, Police Department

a. Detective. This officer had the coat for 2 weeks and wore it five times. He found that he could not wear it while driving and that it was too hot when worn. Moreover, it always looked rumpled as if in need of pressing. He criticized the coat conceptually because reaching for a gun required opening up the whole front, thus exposing a large portion of the torso. His preference for a protective garment type is an undergarment with more stopping power than is provided in the sport coat. He is aware of commercially available protective vests, and although he does not own any protective garment, he does like the idea of lightweight body armor. He stated that he would like to have something he could wear at all times. He did have more confidence while on duty when wearing the coat and would like to continuously have that confidence.

7. Dress Vest - Jacksonville, Florida, Police Department

a. Detective. This officer really liked the vest. He kept it in the back of the car and wore it when he needed it. He had no discomfort, and if there was a heat problem, he did not notice it. His work consisted of apprehending armed robbers. On day duty, there were usually one to three calls a week that required putting on the vest. On night duty, there was at least one call every night. He thinks the vest is a good item and would like to have one all the time. He felt more confident having it on in dangerous situations. His single complaint concerned the buttons that seemed ready to pop off. He would prefer snaps or a false front with the garment fastening to the side.

NOTES

1. N. Montanarelli, C.E. Hawkins, M.A. Goldfarb, and T.F. Ciurej, "Protective Garments for Public Officials," U.S. Army Land Warfare Laboratory Technical Report No. LWL-TR-30B73 (August 1973).
2. "Data Package for Industry/User Symposium on Lightweight Body Armor," Aerospace Corporation (September 1974).
3. "Detailed Requirements Analysis for Protective Garments," MITRE Corporation Working Paper WP-10419 (26 December 1973) (Draft).
4. B. L. Batissta and G. S. Persinger, "Annual Law Enforcement Casualty Summary July 1970 to June 1971," International Association of Chiefs of Police, Gaithersburgh, Md.
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