NISTIR 4895

# A Study to Determine the Most Important Parameters for Evaluating the Resistance of Soft Body Armor to Penetration by Edged Weapons

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Prepared for
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July 1993

# ABOUT THE TECHNOLOGY ASSESSMENT PROGRAM

The Technology Assessment Program is sponsored by the Office of Development, Testing, and Dissemination of the National Institute of Justice (NIJ), U.S. Department of Justice. The program responds to the mandate of the Omnibus Crime Control and Safe Streets Act of 1968, as amended, which created NIJ and directed it to encourage research and development to improve the criminal justice system and to disseminate the results to Federal, State, and local agencies.

The Technology Assessment Program is an applied research effort that determines the technological needs of justice system agencies, sets minimum performance standards for specific devices, tests commercially available equipment against those standards, and disseminates the standards and the test results to criminal justice agencies nationwide and internationally.

The program operates through:

The *Technology Assessment Program Advisory Council* (TAPAC) consisting of nationally recognized criminal justice practitioners from Federal, State, and local agencies, which assesses technological needs and sets priorities for research programs and items to be evaluated and tested.

The *Office of Law Enforcement Standards* (OLES) at the National Institute of Standards and Technology, which develops voluntary national performance standards for compliance testing to ensure that individual items of equipment are suitable for use by criminal justice agencies. The standards are based upon laboratory testing and evaluation of representative samples of each item of equipment to determine the key attributes, develop test methods, and establish minimum performance requirements for each essential attribute. In addition to the highly technical standards, OLES also produces user guides that explain in nontechnical terms the capabilities of available equipment.

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The National Institute of Justice is a component of the Office of Justice Programs, which also includes the Bureau of Justice Assistance, Bureau of Justice Statistics, Office of Juvenile Justice and Delinquency Prevention, and the Office for Victims of Crime.

## ACKNOWLEDGMENTS

This report was prepared by the Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology under the direction of Daniel E. Frank, Manager, Protective Equipment Program, and Lawrence K. Eliason, Director of OLES. The research was sponsored by the Technical Support Working Group through the U.S. Secret Service in conjunction with the National Institute of Justice, David G. Boyd, Director, Science and Technology Division. The technical effort to develop this report was conducted under Interagency Agreement LEAA-J-IAA-021-3, Project No. 9003.

## FOREWORD

The Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology (NIST) furnishes technical support to the National Institute of Justice (NIJ) program to strengthen law enforcement and criminal justice in the United States. OLES's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

OLES is: (1) Subjecting existing equipment to laboratory testing and evaluation and (2) conducting research leading to the development of several series of documents, including national voluntary equipment standards, user guides, and technical reports.

This document covers research on law enforcement equipment conducted by OLES under the sponsorship of NIJ. Additional reports as well as other documents are being issued under the OLES program in the areas of protective equipment, communications equipment, security systems, weapons, emergency equipment, investigative aids, vehicles, and clothing.

Technical comments and suggestions concerning this document are invited from all interested parties. They may be addressed to the Office of Law Enforcement Standards, National Institute of Standards and Technology, Gaithersburg, MD, 20899.

Lawrence K. Eliason, Director
Office of Law Enforcement Standards

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## COMMONLY USED SYMBOLS AND ABBREVIATIONS

| | | | | | |
|---|---|---|---|---|---|
| A | ampere | H | henry | nm | nanometer |
| ac | alternating current | h | hour | No. | number |
| AM | amplitude modulation | hf | high frequency | o.d. | outside diameter |
| cd | candela | Hz | hertz (c/s) | Ω | ohm |
| cm | centimeter | i.d. | inside diameter | p. | page |
| CP | chemically pure | in | inch* | Pa | pascal |
| c/s | cycle per second* | ir | infrared | pe | probable error |
| d | day | J | joule | pp. | pages |
| dB | decibel | L | lambert | ppm | part per million |
| dc | direct current | L | liter | qt | quart* |
| °C | degree Celsius | lb | pound* | rad | radian |
| °F | degree Fahrenheit* | lbf | pound-force* | rf | radio frequency |
| diam | diameter | lbf·in | pound-force inch* | rh | relative humidity |
| emf | electromotive force | lm | lumen | s | second |
| eq | equation | ln | logarithm (natural) | SD | standard deviation |
| F | farad | log | logarithm (common) | sec. | section |
| fc | footcandle* | *M* | molar | SWR | standing wave ratio |
| fig. | figure | m | meter | uhf | ultrahigh frequency |
| FM | frequency modulation | min | minute | uv | ultraviolet |
| ft | foot* | mm | millimeter | V | volt |
| ft/s | foot per second* | mph | mile per hour* | vhf | very high frequency |
| *g* | acceleration | m/s | meter per second | W | watt |
| g | gram | N | newton | λ | wavelength |
| gr | grain* | N·m | newton meter | wt | weight |

area = unit$^2$ (e.g., m$^2$, cm$^2$, etc.); volume = unit$^3$ (e.g., m$^3$, cm$^3$, etc.)

### PREFIXES

| | | | |
|---|---|---|---|
| d | deci ($10^{-1}$) | da | deka (10) |
| c | centi ($10^{-2}$) | h | hecto ($10^{2}$) |
| m | milli ($10^{-3}$) | k | kilo ($10^{3}$) |
| μ | micro ($10^{-6}$) | M | mega ($10^{6}$) |
| n | nano ($10^{-9}$) | G | giga ($10^{9}$) |
| p | pico ($10^{-12}$) | T | tera ($10^{12}$) |

### COMMON CONVERSIONS
(See ASTM E380)

ft/s×0.3048000 = m/s
ft×0.3048 = m
ft·lbf×1.355818 = J
gr×0.06479891 = g
in×2.54 = cm
kWh×3 600 000 = J

lb×0.4535924 = kg
lbf×4.448222 = N
lbf/ft×14.59390 = N/m
lbf·in×0.1129848 = N·m
lbf/in$^2$×6894.757 = Pa
mph×1.609344 = km/h
qt×0.9463529 = L

Temperature: $(T_{°F}-32)\times 5/9 = T_{°C}$

Temperature: $(T_{°C}\times 9/5)+32 = T_{°F}$

*These units are not in the metric system of units, but are included for the convenience of the user.

## SPECIAL ABBREVIATIONS USED IN THIS DOCUMENT

| | |
|---|---|
| Avg. | average |
| Dyn. | dynamic |
| fig. | figure |
| FPE | foamed polyethylene |
| HRC | Hard on the Rockwell C-scale |
| PVC | polyvinyl chloride |
| stat. | static |
| UHMWPE | ultra-high molecular weight polyethylene |
| v. | versus |

# A Study to Determine the Most Important Parameters for Evaluating the Resistance of Soft Body Armor to Penetration by Edged Weapons

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This paper describes tests that were conducted to determine the most important parameters for measuring the resistance of soft body armor to penetration by edged weapons.

Samples consisting of multiple layers of polyaramid fabric were tested against the following variables: blade, geometry, backing material, conditioning, impact angle, and velocity. Stab and slice tests were conducted.

Some commercial armors were also tested. The commercial armors were constructed of ultra-high molecular weight polyethylene, polyaramid fabric, and combinations of ultra-high molecular weight polyethylene, polyaramid fabric, and titanium.

Results indicate that penetration is a strong function of blade geometry. Backing material, conditioning, and impact angle appeared to have only a minimal affect upon the results.

Key words: armor; body armor, edged weapons; penetration; polyaramid; protective clothing; protective equipment.

## I. INTRODUCTION

Soft, concealable body armor has been available since the early seventies when polyaramid fabric was introduced, making concealable ballistic protection with lightweight fabric practical for the first time. During the past two decades there has been considerable evidence to demonstrate the effectiveness of soft body armor against handgun assaults. However, soon after its introduction, questions were raised about the effectiveness of soft body armor against assaults by edged weapons and it wasn't long before "potential users" began stabbing armor samples with a variety of knives and ice picks. This first round of unsophisticated testing suggested that soft body armor did not protect very well against ice picks but offered some protection against attacks with butcher knives. It became apparent

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that there was a need for more sophisticated testing to determine what the most serious threats were, how to measure resistance to penetration, and how well various commercially available materials protect against assaults by edged weapons.

The only current method for testing police armor for resistance to penetration by edged weapons was issued by the H.P. White Laboratory, Inc. It requires a 110 J (81 ft-lb impact with an awl. Any penetration of the back surface of the armor constitutes failure.

Recently, the Technical Support Working Group through the U.S. Secret Service in conjunction with the National Institute of Justice provided joint funding to support a project to define the most serious knife threats, develop test methods, and establish performance criteria for body armor designed for protection against assaults by edged weapons.

### A. Materials

Virtually all of the concealable body armor sold in this country today is made of woven polyaramid fiber, woven ultra-high molecular weight polyethylene (UHMWPE)[1] fiber, or nonwoven ultra-high molecular weight polyethylene. Some manufacturers use combinations of these materials and some add a hard outer layer (usually steel or titanium) to offer greater protection against the more serious ballistic threats or to protect against knife assaults.

### B. Objectives

The project consists of three phases: 1) identify the most important parameters for testing the resistance of body armor to penetration by edged weapons, 2) develop test methods and performance criteria for measuring the resistance of body armor to assault by edged weapons, and 3) prepare a description or specification of a prototype garment to protect against assaults by edged weapons. The ultimate goal is to develop a standard that can be used by law enforcement agencies for procurement of body armor that will provide reasonable protection for the user within realistic constraints of comfort and cost.

## II. APPROACH

### A. Stab Penetration

A test plan was established for a preliminary investigation to determine how various parameters affect soft armor penetration. The experimental design utilizes the Yates order (named for the British statistician Frank Yates who developed it) which allows efficient

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[1]See Special Abbreviations Used in this Document at beginning of report.

analysis of several variables at a time by setting up an overall test matrix. The variables in the matrix are changed one at a time until each required test condition has been evaluated.

Matrix 1, stab penetration test matrix, permits the examination of penetrator geometry (narrow v. wide), backing material (air v. polyethylene foam), impact angle (0 v. 45°), and conditioning (dry v. wet). Since there are four variables each with two conditions, the matrix is known as a $2^4$ design, which requires a total of 16 individual test runs to investigate the effects of each variable upon penetrations. The output parameters are acceleration, force, and penetration. Negative signs represent the first condition; positive signs the second condition.

Samples were tested for stab penetration both quasi-statically and dynamically using the same test matrix. For quasi-static tests, penetrators under load were lowered slowly by hand onto the sample. Dynamic tests were conducted by dropping the penetrator in guided free-fall.

*Matrix 1. Stab penetration test matrix; $2^4$ design*

| Variables | Conditions | |
|---|---|---|
| | - | + |
| Geometry | Narrow | Wide |
| Conditioning | Dry | Wet |
| Backing | Air | P/E |
| Angle | 0 | 45 |

| Run | Blade geometry | Conditioning | Backing | Angle |
|---|---|---|---|---|
| 1 | - | - | - | + |
| 2 | + | - | - | - |
| 3 | - | - | - | + |
| 4 | + | + | + | - |
| 5 | - | - | + | - |
| 6 | + | - | + | + |
| 7 | - | + | - | + |
| 8 | + | + | + | - |
| 9 | - | - | - | + |
| 10 | + | + | - | + |
| 11 | - | - | - | + |
| 12 | + | + | + | - |
| 13 | - | - | + | + |
| 14 | + | - | + | + |
| 15 | - | + | + | + |
| 16 | + | + | + | + |

## B. Slash Penetration

The Yates order was also used to determine the effect of selected variables on armor resistance to penetration by slashing. The variables listed below were examined using a $2^5$ test design (5 variables; 2 conditions):

| | |
|---|---|
| Backing Material | Soft v. Hard |
| Armor Conditioning | Dry v. Wet |
| Blade Velocity | Low v. High |
| Mode | Static v. Dynamic |
| Water Treatment | No v. Yes |

As shown in matrix 2, slash penetration test matrix, a total of 32 individual test runs are necessary to investigate the effects of each variable upon penetration.

# III. TEST APPARATUS

## A. Stab

A guided free-fall apparatus instrumented with a force transducer and accelerometer was constructed as shown in figures 1 through 3. The total mass of the drop carriage, blade, and force transducer was 6.4 kg (14 lbs). Velocity was measured just before impact by a velocimeter consisting of a sensor through which passes a 25 mm (1.00 in) wide flag attached to the platform. The sensor starts a digital timer with the front edge and stops it with the back edge of the flag. Test samples were mounted two ways: (1) on a block of foamed polyethylene [0.035 $gm/cm^3$ (2.2 $lb/ft^3$)] to simulate resistance of the human body and (2) on a frame so that the test area had no backing.

Penetrators: Two penetrators were used for the stab penetration tests to measure the effect of blade geometry on penetration. Both penetrators were dagger-style, machined from D-2 steel and hardened to 55 HRC (55 on the Rockwell C-scale). Dimensions are shown in figure 4 for blades 1 and 2. The shape of the blades was based on preliminary tests with various styles of commercial knives ranging from kitchen knives to stilettos. It was apparent from preliminary tests that the symmetrical geometry of the stiletto or dagger-style blade penetrated armor much more readily than other shapes. Commercial awls were also evaluated and proved to be less penetrating than dagger-style blades.

One of the dagger-type blades had a thick, narrow blade and the other a thin, wide blade (fig. 4). These choices allowed the evaluation of the penetrating effects of two extreme geometries of the most penetrating style blade.

The selection of D-2 steel was based primarily on its excellent wear resistance. The blades were hardened to 55 HRC to provide toughness without making them overly brittle.

During impact, force, acceleration, and time were read out directly on an oscilloscope. The information was then digitized and stored in a computer file.

*Matrix 2. Slash penetration test matrix; $2^5$ design*

| Variables | Conditions | |
|---|---|---|
| | – | + |
| Backing | Soft | Hard |
| Conditioning | Dry | Wet |
| Velocity | Low | High |
| Mode | Stat. | Dyn. |
| Treatment | No | Yes |

| Run | Backing | Conditioning | Velocity | Height | Treatment |
|---|---|---|---|---|---|
| 1 | + | – | – | + | – |
| 2 | + | – | – | + | + |
| 3 | + | + | – | + | – |
| 4 | + | + | – | – | – |
| 5 | + | – | + | + | – |
| 6 | + | – | + | + | – |
| 7 | + | + | + | – | + |
| 8 | + | + | + | – | – |
| 9 | + | + | – | + | – |
| 10 | + | – | – | + | – |
| 11 | + | + | – | + | + |
| 12 | + | + | – | – | – |
| 13 | – | + | + | + | – |
| 14 | + | – | + | + | + |
| 15 | + | + | + | + | + |
| 16 | + | + | + | – | – |
| 17 | + | – | – | + | – |
| 18 | + | – | – | + | + |
| 19 | – | + | – | + | + |
| 20 | + | + | – | – | – |
| 21 | + | + | + | + | – |
| 22 | + | – | + | + | – |
| 23 | + | + | + | – | + |
| 24 | + | + | + | – | + |
| 25 | + | – | – | + | – |
| 26 | + | – | – | + | + |
| 27 | + | + | – | + | – |
| 28 | + | + | – | – | – |
| 29 | – | – | + | + | + |
| 30 | + | – | + | + | + |
| 31 | – | + | + | + | + |
| 32 | + | + | + | + | + |

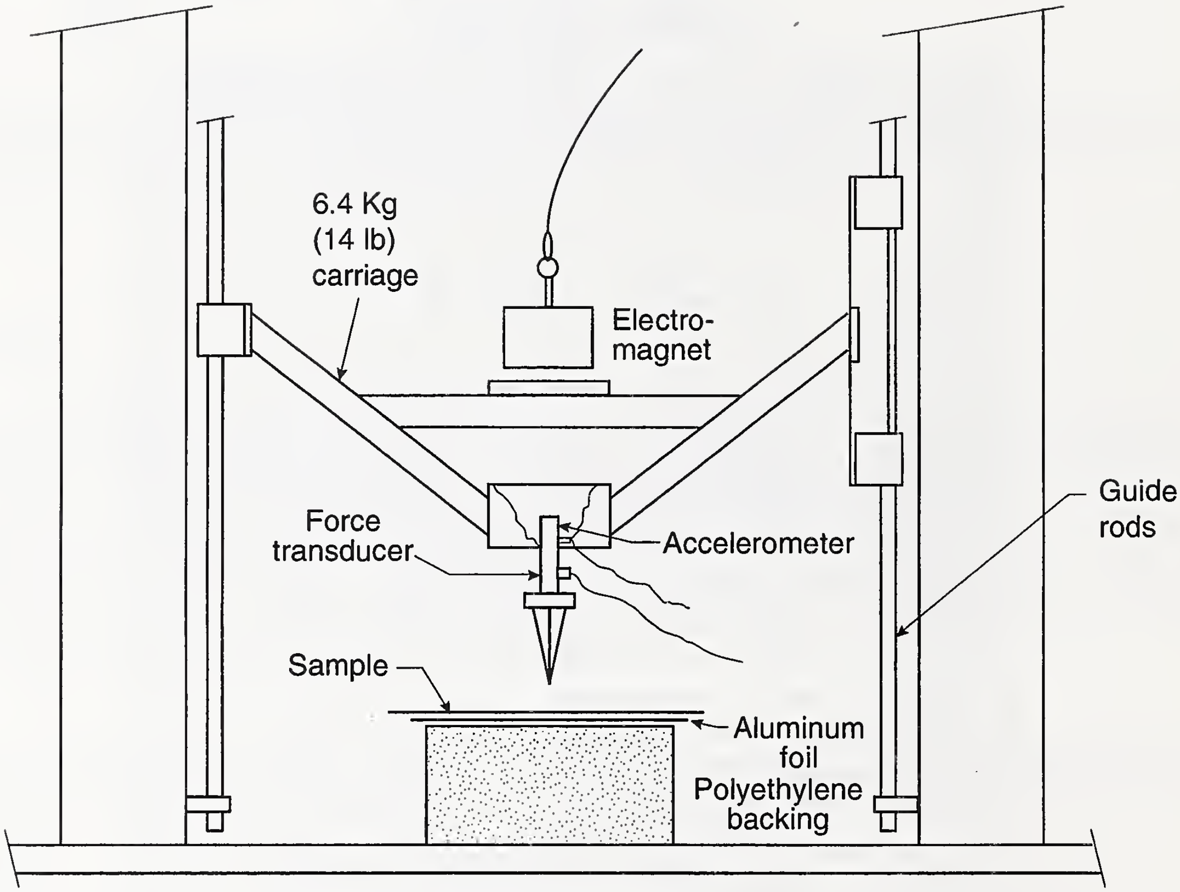



Figure 1. Sketch of free fall test apparatus

*Figure 1. Sketch of free fall test apparatus.*

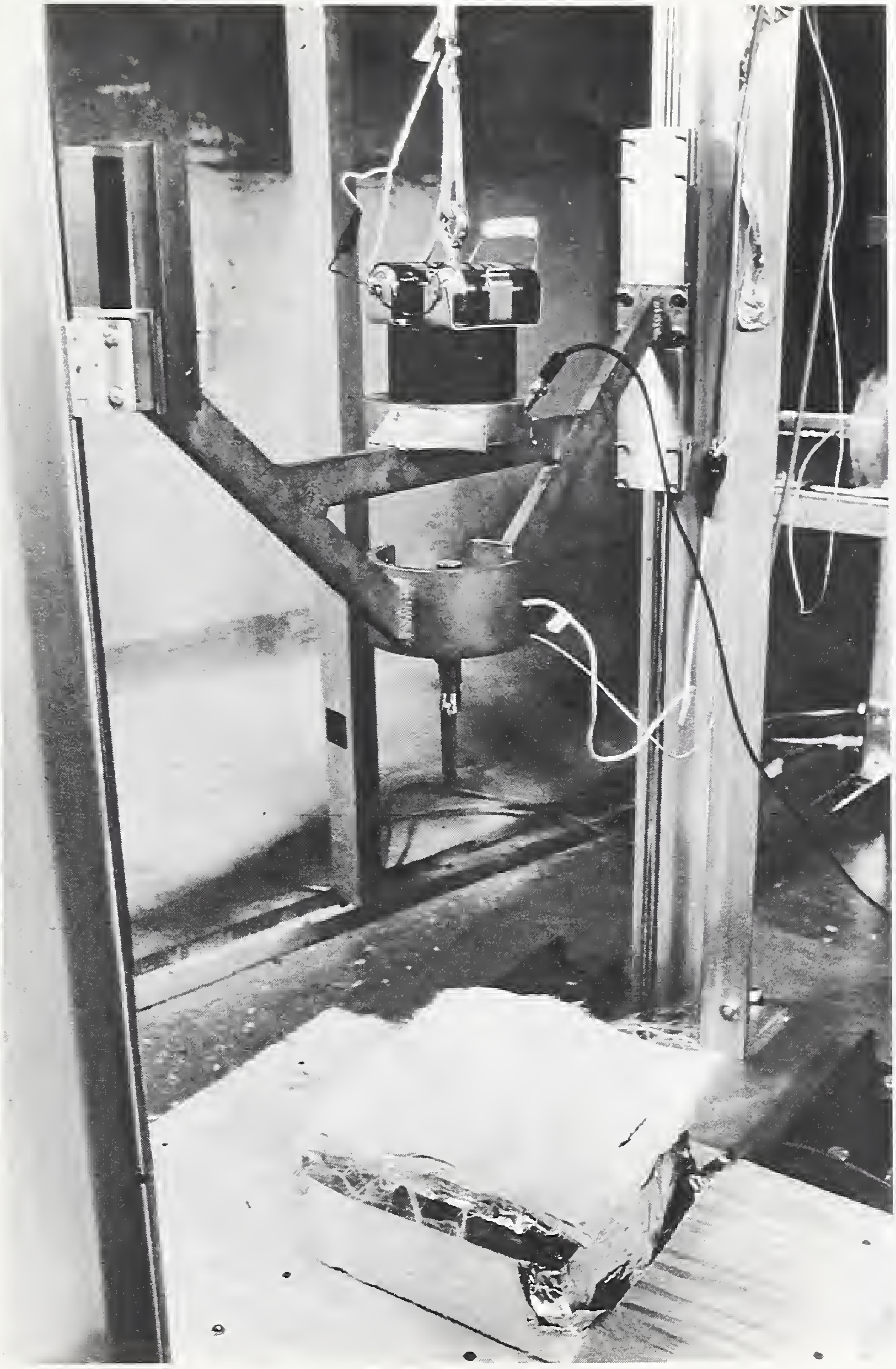


*Figure 2. Photograph of carriage suspended above sample by electromagnet.*

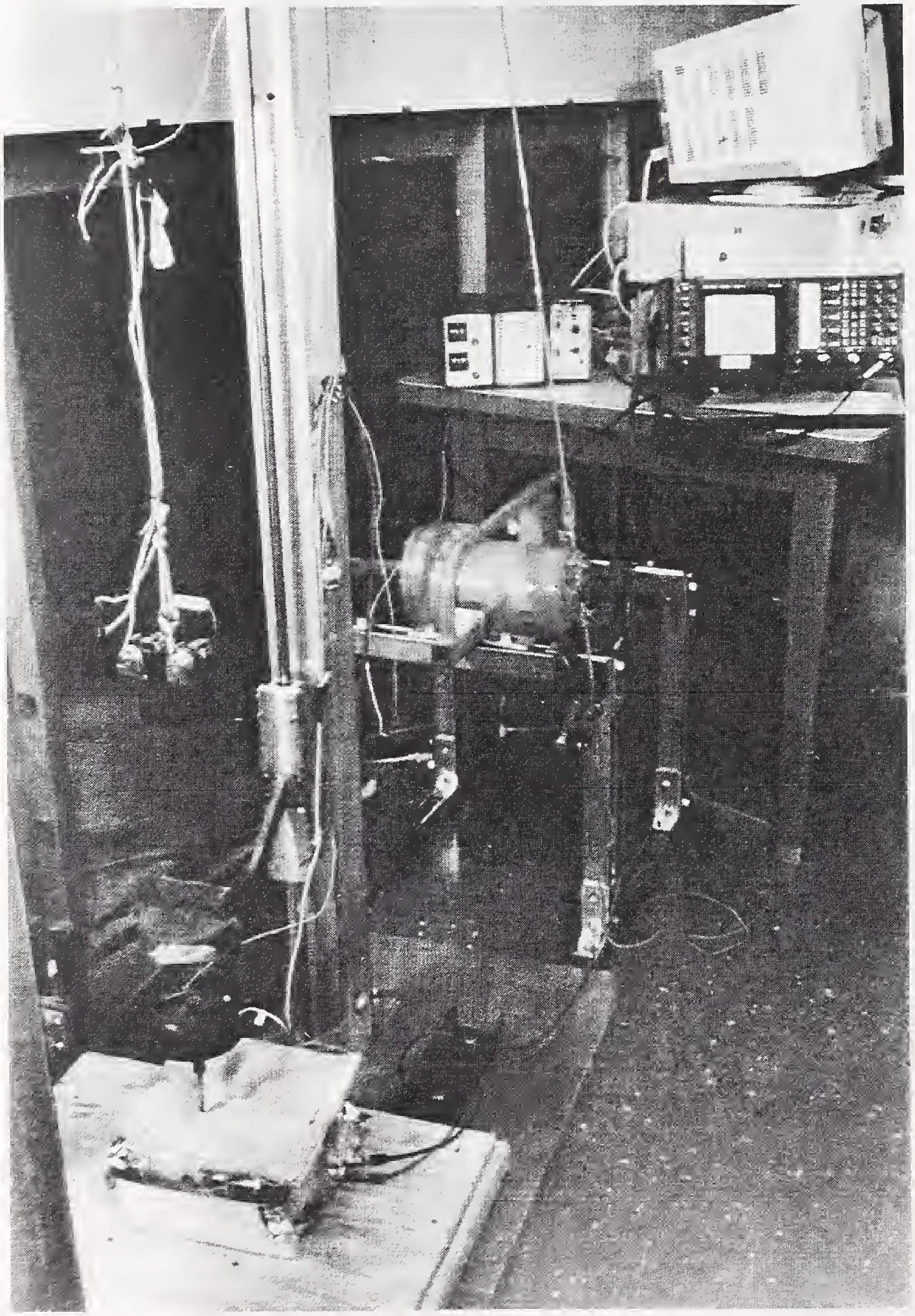


*Figure 3. Photograph of overall apparatus used for stab penetration testing.*

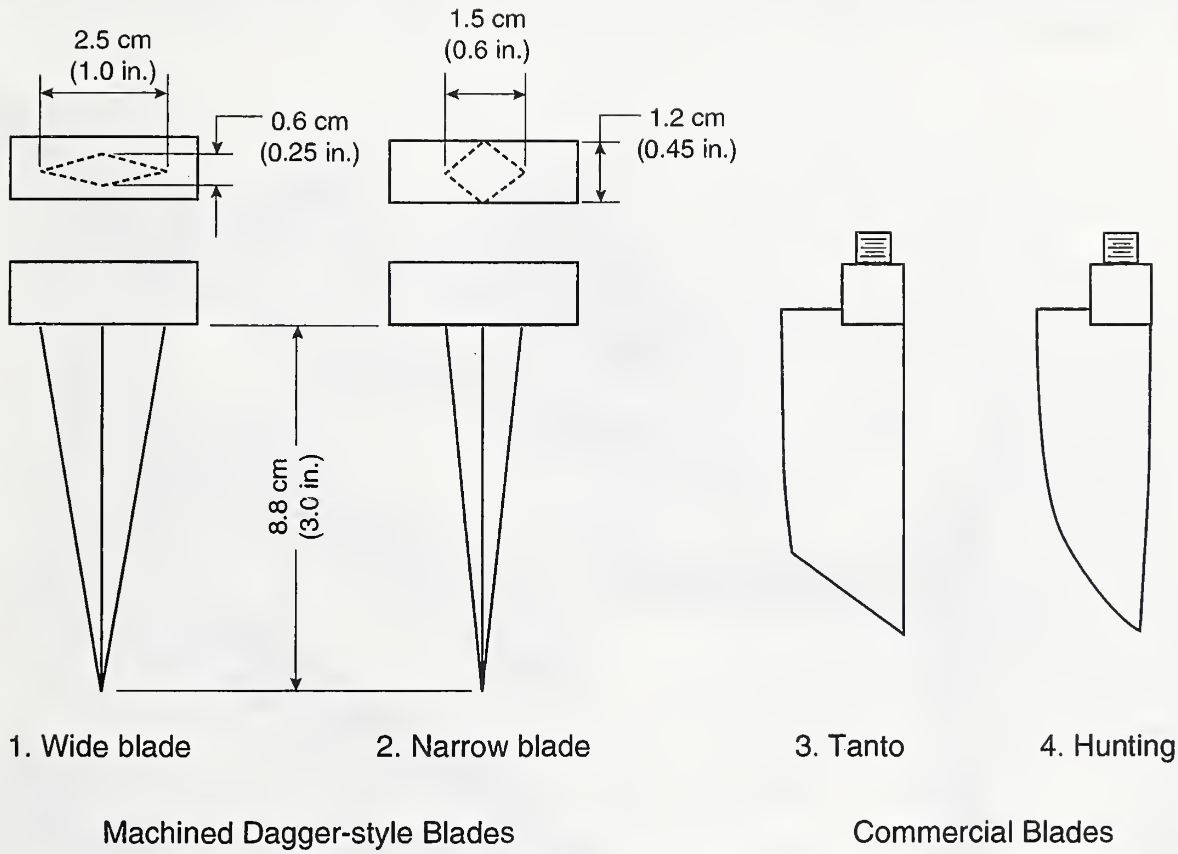



*Figure 4. Test penetrators.*

## B. Slash

The test apparatus shown in figures 5 and 6 consists of a blade (shown in figure 7) mounted above a movable table. The blade pivots so that it can be brought into contact with a test sample mounted on the table. Dimensions of the blade are based on representative samples of commercial knives. Test samples are mounted on a foamed polyethylene rod or rigid pvc cylinder, both 10 cm (4 in) in diameter and fastened to the table. A pneumatic cylinder operated from compressed gas propels the table forward at a pre-selected velocity which is adjusted by a flow control valve. The table moves a distance of 19 cm (7.5 in). The velocity of the table is measured in the same manner and with the same velocimeter as was used in the drop tests.

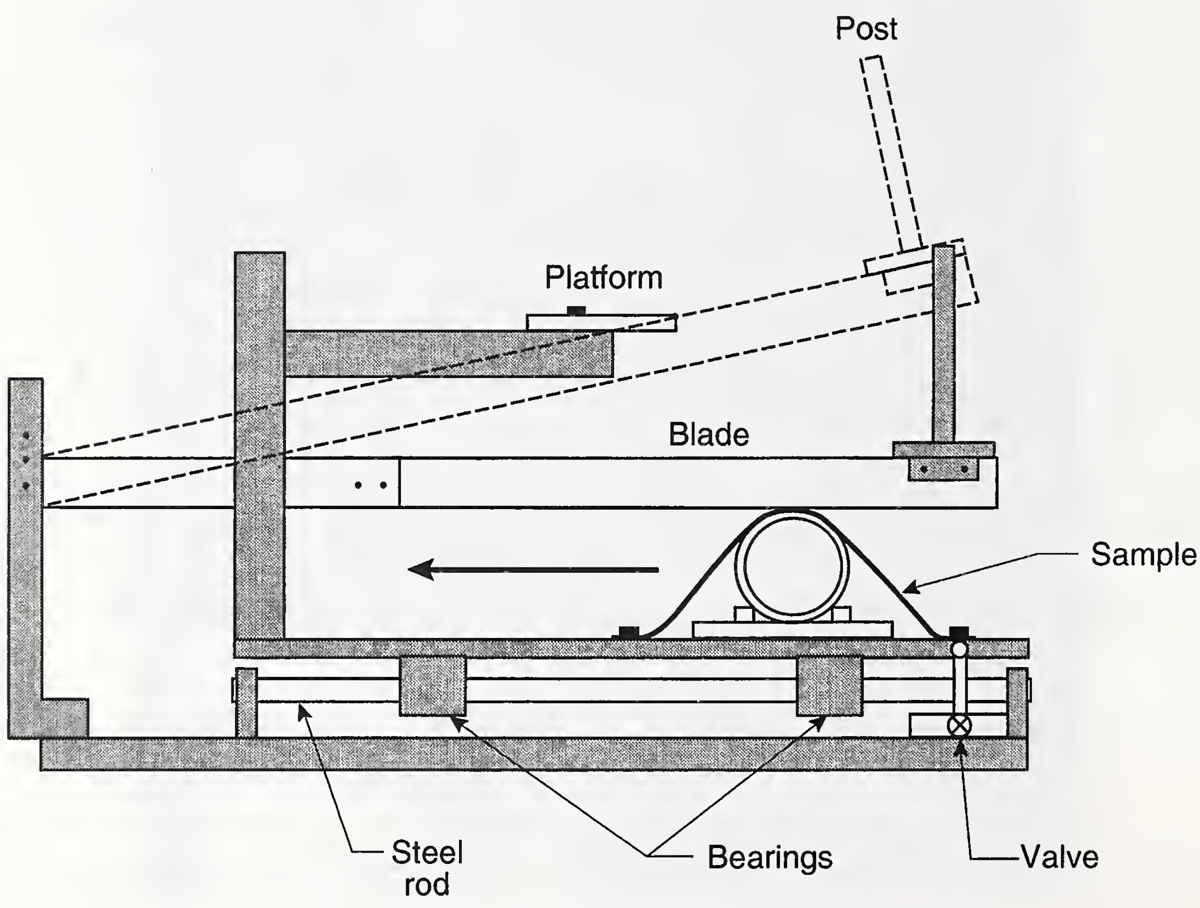



*Figure 5. Sketch of slash test apparatus.*

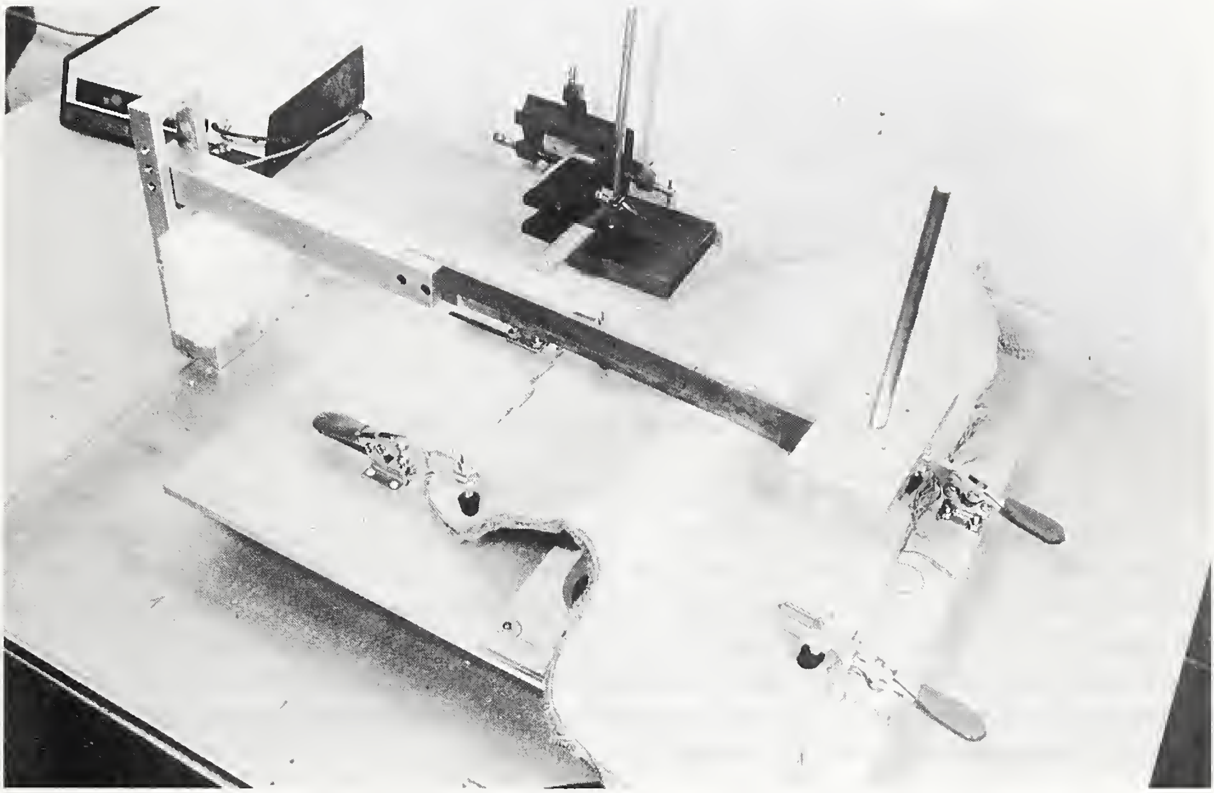


*Figure 6. Photograph of slash test apparatus.*

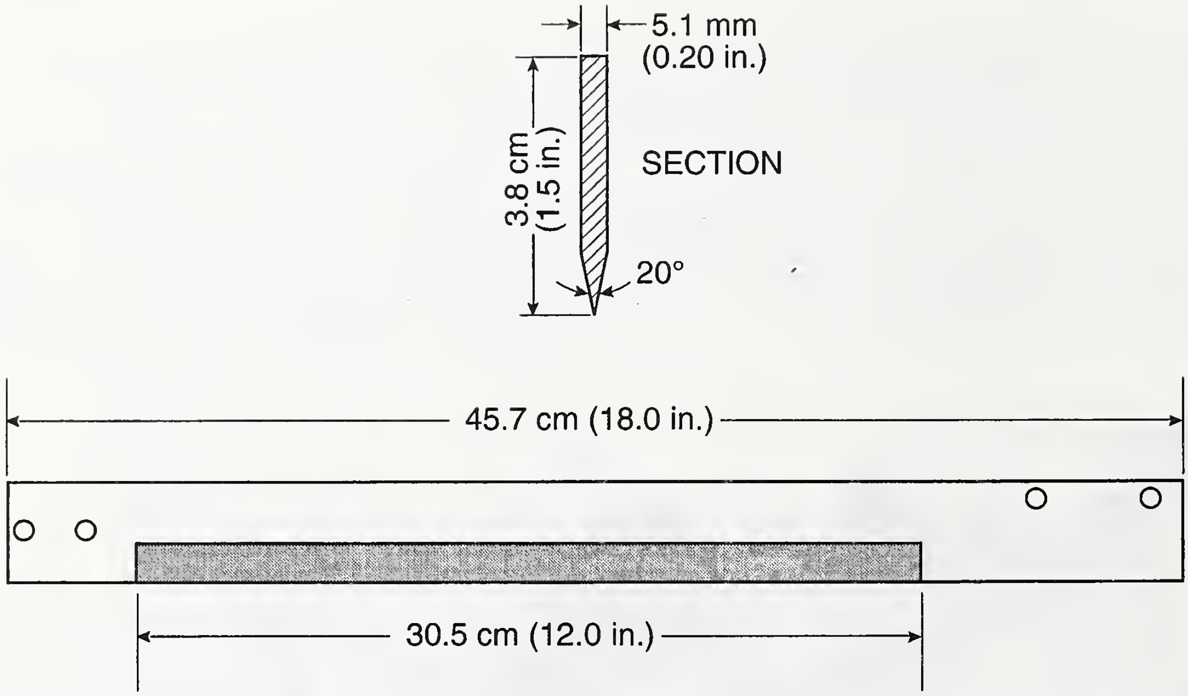



*Figure 7. Sketch of slash test blade.*

The sample can be tested in a dynamic (impact plus slice) or static (slice only) mode. For static tests the blade rests on the sample and the table is moved forward by the pneumatic cylinder; dynamic tests are performed by raising the blade 10 cm (4 in) onto the platform shown in figure 4 prior to release of the table. As the table is moved forward, the blade drops onto the sample so that the blade impacts the sample while it is moving. In both tests, the effective mass of the blade can be increased by adding weights to the post attached to the free end of the blade (fig. 8).

## IV. TEST PROCEDURE AND RESULTS

### A. Stab Penetration Test

1. Static

A series of tests were conducted quasi-statically by lowering the penetrator attached to a 6.4 kg (14 lb) carriage by hand onto soft armor samples. The force-time trace was saved on an oscilloscope and examined to determine the course of penetration. Initially, the

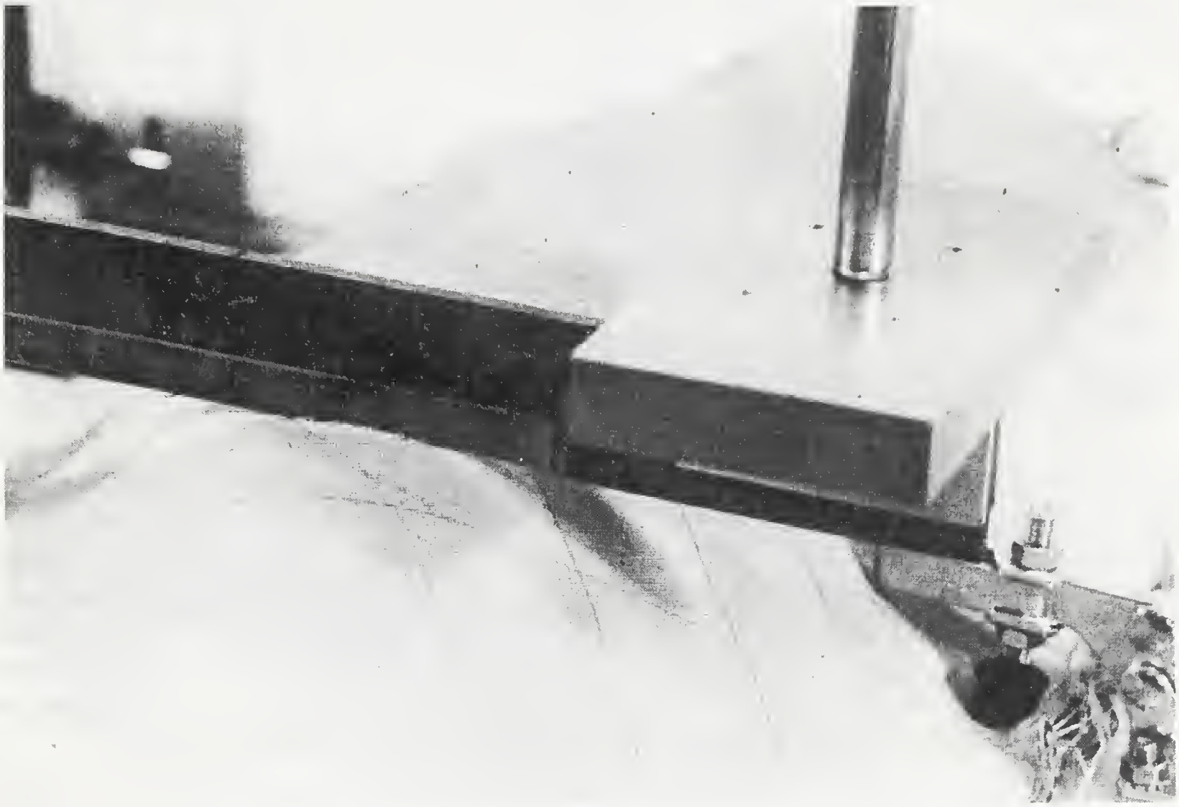


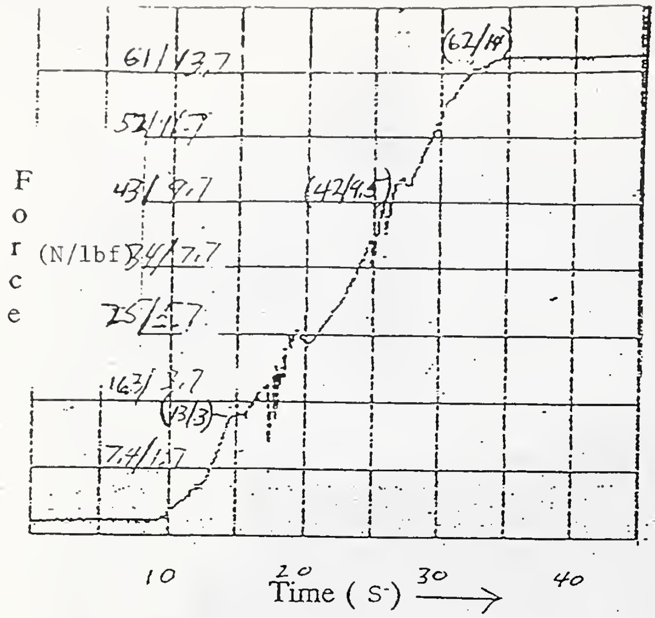
*Figure 8. Photograph of post used to add weight to slash test blade.*

tests were conducted on 32 layers of polyaramid fabric (840 denier, 31 x 31 plain weave) using a narrow, dagger-type blade. Conditioning (wet, dry), backing (air, foamed polyethylene) and penetration angle (0, 45°) were adjusted to determine whether and to what extent they affected the outcome. Typical traces of the force-time curves are shown in figure 9.

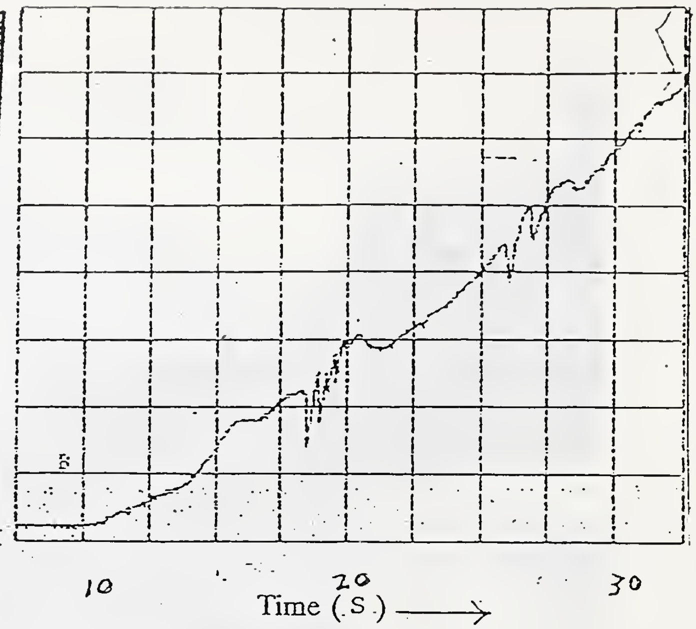
Since no complete penetration occurred with 32 layers (table 1), a second series was conducted using 24 layers of the same polyaramid fabric for a more discriminating test. In addition to conditioning, backing and angle of penetration, blade geometry was also varied (narrow v. wide) in the second test series (table 2).

2. Dynamic

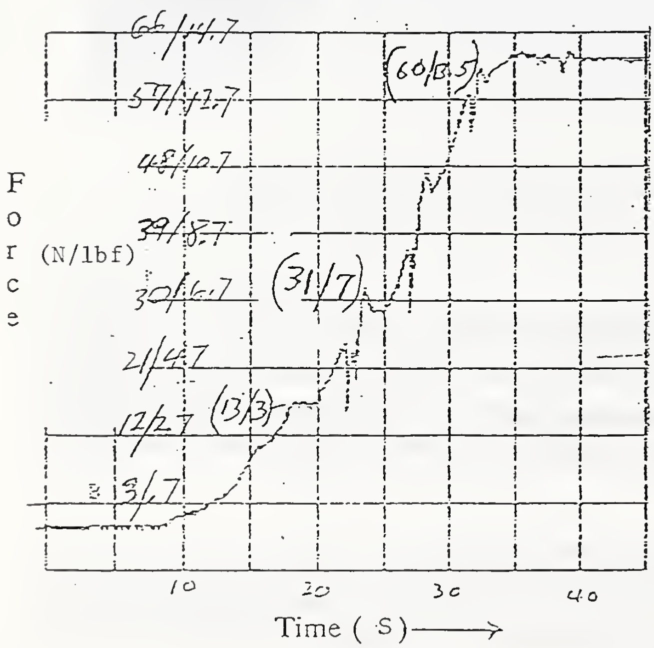
The dynamic tests were conducted by releasing the instrumented penetrator attached to the carriage from an electromagnet at a predetermined drop-height onto the sample and



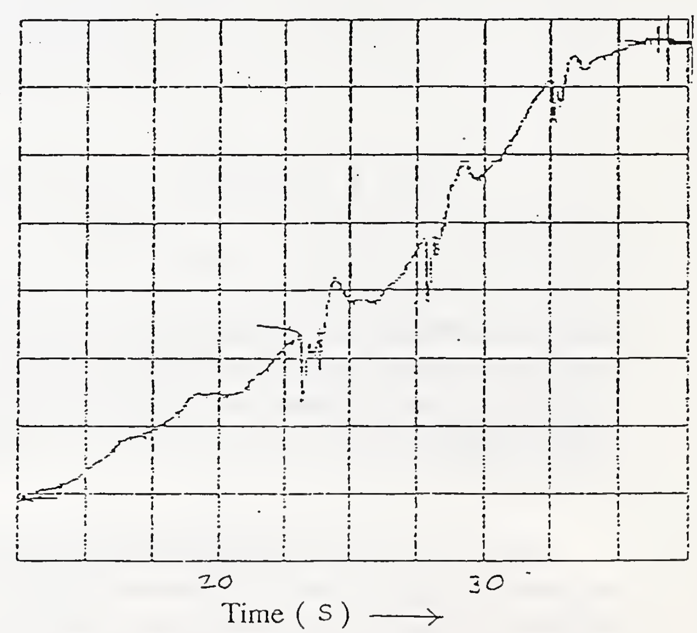

a. Dry sample.




b. x axis enlarged 2x.




c. Wet sample.




d. x axis enlarged 2x.

*Figure 9. Quasi-static stab penetration test; 32 layers polyaramid fabric. Dagger style machined blade; foamed polyethylene backing; 0° impact angle.*

recording the force-time curve on an oscilloscope. To determine whether full penetration occurred, aluminum foil was placed under the test sample (see fig. 1) and connected electrically to the penetrator. A signal device was placed in the circuit so that an electrical connection lasting 1 ms or longer would activate the circuit. Twenty-four layers of 840 denier, 31 x 31 plain weave polyaramid were used for the first dynamic test while varying blade geometry (narrow, wide), conditioning (dry, wet) backing (air, foamed polyethylene) and angle (0, 45°). The drop height was 0; that is, the carriage was lowered slowly until the penetrator just made contact with the sample, held momentarily with an electromagnet and released. Data taken with this method is labeled "free-fall; height = 0" (table 3).

A second series of tests was conducted using 32 layers of the same polyaramid fabric, but since full penetration occurred readily in all cases, the sample was finally increased to 40 layers for better discrimination (table 4).

In addition to the machined blades (numbered 1 and 2 in fig. 4), commercial blades (numbered 3 and 4 in fig. 4) were tested to measure armor resistance to penetrators with different geometries. Blade 4 is representative of a hunting style knife (table 5) and blade 3 represents a configuration known as "Tanto" (table 6) which is reported to be designed for penetration. Dynamic penetration tests were also conducted on selected currently available commercial armors. Table 7 gives a description of the commercial armors tested and the test results.

*Table 1. Static stab penetration test; 32 layers polyaramid fabric; narrow blade; 62 N (14 lbf)*

| Variables | Conditions | |
|---|---|---|
| | – | + |
| Conditioning | Dry | Wet |
| Backing | Air | P/E |
| Angle | 0 | 45 |

| Run | Conditioning | Backing | Angle | N to start penetration | Lbf to start penetration |
|---|---|---|---|---|---|
| 1 | – | + | – | 15, 18, 15 | 3.4, 4.1, 3.3 |
| 2 | + | + | – | 23, 35, 29 | 5.1, 7.8, 6.5 |
| 3 | – | + | – | 15, 28, 17 | 3.3, 6.2, 3.8 |
| 4 | + | + | – | 24, 44, 24 | 5.4, 9.8, 5,3 |
| 5 | – | – | + | 8.0, 8.4, 9.9 | 1.8, 1.9, 2.2 |
| 6 | + | – | + | 16.9, 8.9, 13.8 | 3.8, 2.0, 3.1 |
| 7 | – | + | + | 12.9, 32, 11.1 | 2.9, 7.2, 2.5 |
| 8 | + | + | + | 8.4, 11.6, 16.0 | 1.9, 2.6, 3.6 |

*Table 2. Static stab penetration test;*
*24 layers polyaramid fabric; static*

| Variables | Conditions | |
|---|---|---|
| | – | + |
| Geometry | Narrow | Wide |
| Conditioning | Dry | Wet |
| Backing | Air | P/E |
| Angle | 0 | 45 |

| Run | Blade geometry | Conditioning | Backing | Angle | Force to penetrate | |
|---|---|---|---|---|---|---|
| | | | | | (N) | (lbf) |
| 1 | – | – | – | – | 49 | 10.8 |
| 2 | + | – | – | – | 42 | 9.4 |
| 3 | – | + | – | – | 57 | 12.7 |
| [illegible] | + | + | – | – | 44 | 9.8 |
| 5 | – | + | – | – | 48 | 10.8 |
| 6 | + | – | + | – | 44 | 9.8 |
| 7 | – | + | – | – | No penetration | |
| 8 | + | – | + | + | 50 | 11.3 |
| 9 | – | + | – | – | 48 | 10.8 |
| 10 | + | – | – | + | 49 | 10.9 |
| 11 | – | + | – | – | 57 | 12.9 |
| 12 | + | – | – | + | 44 | 9.9 |
| 13 | – | – | + | + | 50 | 11.3 |
| 14 | + | – | + | + | 41 | 9.3 |
| 15 | – | + | + | + | 58 | 13.0 |
| 16 | + | + | + | + | 43 | 9.6 |

*Table 3. Dynamic stab penetration test;*
*24 layers polyaramid fabric; free fall; height = 0*

| Variables | Conditions | |
|---|---|---|
| | - | + |
| Blade | Narrow | Wide |
| Conditioning | Dry | Wet |
| Backing | Air | P/E |
| Angle | 0 | 45 |

| Run | Blade geometry | Conditioning | Backing | Angle | Penetration depth* | | Force to penetrate | |
|---|---|---|---|---|---|---|---|---|
| | | | | | (cm) | (in) | (N) | (lbf) |
| 1 | − | − | − | − | 2.5 | 1 | 61 | 13.8 |
| 2 | + | − | − | − | To hilt | | 52 | 11.6 |
| 3 | − | − | − | − | 2.5 | 1 | 98 | 22 |
| 4 | + | − | − | − | To hilt | | 53 | 12 |
| 5 | − | − | + | − | 3.1 | 1 1/4 | 53 | 12 |
| 6 | + | − | + | − | 4.4 | 1 3/4 | 52 | 11.6 |
| 7 | − | + | + | − | 2.5 | 1 | 62 | 14 |
| 8 | + | + | + | − | 3.8 | 1 1/2 | 53 | 12 |
| 9 | − | − | − | − | 3.8 | 1 1/2 | 58 | 14 |
| 10 | + | − | − | + | To hilt | | 45 | 10 |
| 11 | − | − | − | − | 3.1 | 1 1/4 | 55 | 12.4 |
| 12 | + | + | − | + | 3.8 | 1 1/2 | 60 | 13.5 |
| 13 | − | − | + | + | 2.9 | 1 1/8 | 53 | 12 |
| 14 | + | − | + | + | 3.1 | 1 1/4 | 45 | 10 |
| 15 | − | + | + | + | 3.1 | 1 1/4 | 55 | 12.4 |
| 16 | + | + | + | + | To hilt | | 49 | 11 |

*Length of blade exiting back surface.

*Table 4. Dynamic stab penetration test; 40 layers polyaramid fabric; free fall; height = 0; dry*

| Variables | Conditions | |
|---|---|---|
| | – | + |
| Blade | Narrow | Wide |
| Back | Air | P/E |
| Angle | 0 | 45 |

| Run | Blade geometry | Backing | Angle | Force to penetrate | | Penetration depth* | |
|---|---|---|---|---|---|---|---|
| | | | | (N) | (lbf) | (cm) | (in) |
| 1 | – | – | – | 116 | 26 | 2.2 | 7/8 |
| 2 | + | – | – | 98 | 22 | 2.9 | 1 1/8 |
| 3 | – | + | – | 80 | 18 | 2.2 | 7/8 |
| 4 | + | – | – | 98 | 22 | 2.2 | 7/8 |
| 5 | – | – | + | 134 | 30 | 2.9 | 1 1/8 |
| 6 | + | – | + | 129 | 29 | 2.9 | 1 1/8 |
| 7 | – | + | + | 111 | 25 | 2.2 | 7/8 |
| 8 | + | + | + | 134 | 30 | 2.4 | 15/16 |

*Length of blade exiting back surface.

*Table 5. Dynamic stab penetration test; hunting blade; 40 layers polyaramid fabric*

| Run | Height | | Energy | | Velocity | | Applied force | | Penetration depth* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (cm) | (in) | (J) | (ft-lbs) | (m/s) | (ft/s) | (N) | (lbf) | (cm) | (in) |
| 1 | 15 | 6 | 10 | 7 | 1.6 | 5.4 | 534 | 120 | 3.0 | 1.2 |
| 2 | 13 | 5 | 8 | 5.8 | 1.5 | 5.0 | 512 | 115 | No penetration | |
| 3 | 15 | 6 | 10 | 7 | 1.7 | 5.5 | 498 | 112 | 3.6 | 1.4 |
| 4 | 13 | 5 | 8 | 5.8 | — | — | 512 | 115 | No penetration | |

*Length of blade exiting back surface.

*Table 6. Dynamic stab penetration test; Tanto blade; 40 layers polyaramid fabric*

| Run | Height | | Energy | | Velocity | | Applied force | | Penetration depth* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (cm) | (in) | (J) | (ft-lbs) | (m/s) | (ft/s) | (N) | (lbf) | (cm) | (in) |
| 1 | 13 | 5 | 8 | 5.8 | 1.7 | 4.8 | 614 | 138 | No penetration | |
| 2 | 15 | 6 | 10 | 7 | 1.3 | 5.2 | 690 | 155 | No penetration | |
| 3 | 18 | 7 | 11 | 8.2 | 1.7 | 5.6 | 668 | 150 | No penetration | |
| 4 | 20 | 8 | 13 | 9.3 | 1.8 | 6.1 | 779 | 175 | No penetration | |
| 5 | 23 | 9 | 14 | 10.5 | 1.9 | 6.4 | 801 | 180 | No penetration | |
| 6 | 25 | 10 | 16 | 11.6 | 2.0 | 6.8 | 757 | 170 | No penetration | |
| 7 | 28 | 11 | 17 | 12.8 | 2.1 | 7.2 | 823 | 185 | No penetration | |
| 8 | 38 | 15 | 24 | 18 | 2.5 | 8.4 | — | — | No penetration | |

*Length of blade exiting back surface.

*Table 7. Stab penetration tests; commercial body armor; wide blade*

| | | Drop height | | Penetration depth* | | Force to penetrate | |
|---|---|---|---|---|---|---|---|
| | | (cm) | (in) | (cm) | (in) | (N) | (lbf) |
| 1 | Model A (SS) | 0 | 0 | 3.5 | 1 3/8 | 93 | 21 |
| 2 | Model D | 0 | 0 | 0.95 | 3/8 | 100 | 22.5 |
| 3 | Model B | 0 | 0 | No penetration | | | |
| 4 | Model B | 2.5 | 1 | 0.95 | 3/8 | 100 | 44 |
| 5 | Model E | 0 | 0 | No penetration | | | |
| 6 | Model F | 20 | 8 | No penetration; blade broke | | | |
| 7 | Model C | 0 | 0 | No penetration | | | |
| 8 | Model C | 2.5 | 1 | 0.95 | 3/8 | 200 | 45 |
| 9 | Model E | 0 | 0 | No penetration | | | |
| 10 | Model E | 20 | 8 | No penetration; blade broke | | | |

*Length of blade exiting back surface.

## Description of Commercial Body Armor

| | |
|---|---|
| Model A | 16 layers woven aramid fabric |
| Model B | 10 layers UHMWPE fabric<br>20 layers nonwoven UHMWPE<br>10 layers UHMWPE fabric |
| Model C | 10 layers quilted UHMWPE fabric<br>30 layers nonwoven UHMWPE<br>10 layers quilted UHMWPE fabric |
| Model D | Double panels of 7 layers of aramid fabric. Total 14 layers front and back |
| Model E | 5 titanium plates 0.30 mm (.012 in) thick between 2 layers aramid fabric; 6 mm (1/4 in) foamed polyethylene comfort pad |
| Model F | 1.3 mm (0.050 in) titanium plate with felt covers |

During penetration testing of these armors, it became apparent that blades machined of D-2 steel would not withstand impacts with the hard materials found in some commercial constructions.

A variety of commercial awls was tested in a search for a penetrator that would defeat the hard armor (or at least impact it without being damaged) and approximate the performance of machined blades on soft armor.

**B. Slash Penetration Test**

Preliminary tests were conducted on eight layers of aramid fiber using a $2^{5-1}$ test design.[2] A $2^{5-1}$ test design systematically examines five variables but, unlike the $2^5$ design which requires 32 runs ($2^5$), the $2^{5-1}$ design requires only 16 runs ($2^4$). The $2^{5-1}$ matrix is established by treating four variables as in a $2^4$ design. The test condition (+ or −) of the fifth variable, in this case treatment, is determined through multiplication of the + and − signs of the test conditions for the other four variables in the test run: for example, +,+,−,+ equals minus and +,−,+,− equals plus. It is especially suitable for preliminary tests such as these to determine the most significant variables and appropriate test conditions. The following variables were examined:

Backing:
- Soft — Four-inch diameter foamed low density polyethylene rod.
- Hard — Four-inch diameter rigid PVC pipe with 63 mm (1/4 in) wall

Conditioning:
- Dry — Room temperature at 50% relative humidity.
- Wet — Submersed in water for 5 min and allowed to drip dry just before testing.

Velocity:
- Low — 0.9 m/s (3 ft/s)
- High — 3 m/s (10 ft/s)

Load:
- Static — Blade rests on sample throughout test.
- Dynamic — Blade is dropped onto sample from 10 cm (4 in) height as table begins its forward motion.

Treatment:
- No — Sample material is untreated.
- Yes — Sample material is factory-treated to repel water.

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[2]Chapter 12, Statistics for Experimenters, Box, George E. P. et al., Hunter & Hunter.

All tests were conducted with a 30 cm (12 in) blade machined from D-2 steel and hardened to 55 HRC (fig. 7). The results are presented in table 8.

Only two of the runs fully penetrated the eight layer sample. In an effort to increase the sensitivity of the test for the variables involved, a second series of tests were conducted on four layers of the same aramid fabric, using a $2^5$ test design (table 9).

*Table 8. Slash test; eight layers polyaramid fabric; $2^{5-1}$ design*

| Variables | Conditions | |
|---|---|---|
| | – | + |
| Backing | Soft | Hard |
| Conditioning | Dry | Wet |
| Velocity | Low | High |
| Mode | Stat. | Dyn. |
| Treatment | No | Yes |

| Run | Backing | Conditioning | Velocity | Height | Treatment | Velocity | | Number of layers cut |
|---|---|---|---|---|---|---|---|---|
| | | | | | | (m/s) | (ft/s) | |
| 1 | – | – | – | – | + | 0.45 | 1.5 | 1 |
| 2 | + | – | + | – | – | 0.45 | 1.5 | 2 |
| 3 | – | + | – | – | – | 0.39 | 1.3 | 1 |
| 4 | + | – | – | – | – | 0.45 | 1.5 | 3 |
| 5 | – | – | – | – | – | 1.4 | 4.8 | 2 |
| 6 | + | – | + | – | – | 1.4 | 4.7 | 5 |
| 7 | – | + | + | – | – | 1.5 | 4.9 | 3 |
| 8 | + | + | + | – | – | 1.5 | 4.9 | 5 |
| 9 | – | – | – | + | – | 0.45 | 1.5 | 1 |
| 10 | + | – | – | – | – | 0.45 | 1.5 | 3 |
| 11 | – | + | – | + | + | 0.4 | 1.4 | 1 |
| 12 | + | + | – | – | – | 0.4 | 1.4 | 3 |
| 13 | – | – | + | + | + | 1.4 | 4.7 | 3 |
| 14 | + | – | + | + | – | 1.5 | 5.0 | 8 |
| 15 | – | + | + | + | – | 1.4 | 4.8 | 5 |
| 16 | + | + | + | + | + | 1.5 | 4.9 | 8 |

*Table 9. Slash test; four layers polyaramid fabric; $2^5$ design*

| Variables | Conditions – | Conditions + |
|---|---|---|
| Backing | Soft | Hard |
| Conditioning | Dry | Wet |
| Velocity | Low | High |
| Mode | Stat. | Dyn. |
| Treatment | No | Yes |

| Run | Backing | Conditioning | Velocity | Height | Treatment | Velocity (m/s) | Velocity (ft/s) | Number of layers cut |
|---|---|---|---|---|---|---|---|---|
| 1 | + | – | – | – | – | 0.51 | 1.7 | 2 |
| 2 | + | – | – | – | – | 0.51 | 1.7 | 4 |
| 3 | – | + | – | – | – | 0.48 | 1.8 | 3 |
| 4 | + | + | – | – | – | 0.54 | 1.8 | 4 |
| 5 | + | – | + | – | – | 1.4 | 4.6 | 2 |
| 6 | + | – | + | – | – | 1.4 | 4.7 | 4 |
| 7 | – | + | + | – | – | 1.4 | 4.6 | 3 |
| 8 | – | + | + | – | – | 1.4 | 4.6 | 4 |
| 9 | + | – | – | – | + | 0.45 | 1.5 | 1 |
| 10 | + | – | – | – | – | 0.54 | 1.8 | 4 |
| 11 | – | + | – | – | – | 0.54 | 1.8 | 0 |
| 12 | + | + | – | – | – | 0.54 | 1.8 | 4 |
| 13 | + | – | + | – | + | 1.4 | 4.6 | 0 |
| 14 | – | – | + | – | – | 1.5 | 5.0 | 4 |
| 15 | – | + | + | – | – | 1.4 | 4.8 | 3 |
| 16 | + | + | + | – | – | 1.5 | 5.0 | 4 |
| 17 | + | – | – | – | + | 0.54 | 1.8 | 0 |
| 18 | + | – | – | – | + | 0.57 | 1.8 | 4 |
| 19 | – | + | – | – | + | 0.51 | 1.7 | 2 |
| 20 | + | – | – | – | + | 0.57 | 1.8 | 4 |
| 21 | + | – | + | – | + | 1.4 | 4.6 | 0 |
| 22 | + | – | + | – | + | 1.4 | 4.6 | 4 |
| 23 | – | – | + | – | + | 1.4 | 4.6 | 2 |
| 24 | + | – | + | – | + | 1.4 | 4.8 | 4 |
| 25 | + | – | – | – | + | 0.51 | 1.7 | 0 |
| 26 | + | – | – | – | + | 0.60 | 2.0 | 4 |
| 27 | – | + | + | – | + | 0.54 | 1.8 | 4 |
| 28 | + | + | – | – | + | 0.57 | 1.8 | 4 |
| 29 | + | – | + | – | + | 1.4 | 4.8 | 2 |
| 30 | + | – | + | – | + | 1.5 | 5.0 | 4 |
| 31 | – | + | + | + | + | 1.4 | 4.8 | 2 |
| 32 | + | + | + | + | + | 1.5 | 4.9 | 4 |

A third series of tests was conducted with eight layers of aramid fabric and a hard backing using a $2^4$ design (table 10). In preliminary testing a soft backing was tried as well as a hard backing. The thought was that a soft backing would be a closer simulation of a human behind the fabric especially over the abdominal area. However, so few layers of fabric were cut that it was the observation of the author that the hard backing was the more severe test and should be used for further testing.

To quantitatively determine the effect of changing the static load on the blade, a series of tests was run with the load on the blade set at 18 N (4 lbf) and at 45 N (10 lbf). The

*Table 10. Slash test; eight layers polyaramid fabric; hard backing; $2^4$ design*

| Variables | Conditions | |
|---|---|---|
| | − | + |
| Conditioning | Dry | Wet |
| Velocity | Low | High |
| Mode | Stat. | Dyn. |
| Treatment | No | Yes |

| Run | Conditioning | Velocity | Height | Treatment | Velocity | | Number of layers cut |
|---|---|---|---|---|---|---|---|
| | | | | | (m/s) | (ft/s) | |
| 1 | − | − | − | + | 0.57 | 1.8 | 2 |
| 2 | + | − | + | − | 0.51 | 4.7 | 3 |
| 3 | − | − | − | + | 1.4 | 4.7 | 3 |
| 4 | + | + | − | − | 1.4 | 4.7 | 2 |
| 5 | − | + | − | + | 0.45 | 1.5 | 8 |
| 6 | + | − | + | − | 0.57 | 1.9 | 8 |
| 7 | − | + | − | + | 1.6 | 5.4 | 8 |
| 8 | + | + | + | − | 1.5 | 5.1 | 8 |
| 9 | − | − | − | + | 0.54 | 1.8 | 2 |
| 10 | + | − | + | − | 0.51 | 1.8 | 2 |
| 11 | − | − | − | + | 1.4 | 1.8 | 3 |
| 12 | + | + | + | − | 1.4 | 1.8 | 2 |
| 13 | − | − | + | + | 0.54 | 1.8 | 8 |
| 14 | + | − | + | + | 0.57 | 1.9 | 8 |
| 15 | − | + | + | + | 1.5 | 5.1 | 8 |
| 16 | + | + | + | + | 1.5 | 5.0 | 8 |

additional parameters were: Conditioning, Dry/Wet; Velocity, low/high; and Treatment (waterproofing), no/yes. The results are presented in table 11.

Finally, tests were conducted on commercial armor with two different constructions:

a. Ten layers of nonwoven UHMWPE in the middle between two 10 layer panels of UHMWPE fabric. Each of the woven fabric panels were stabilized by sewing through all 10 layers with a box pattern called quilting. The woven cloth was made from 215 denier yarn, 56 x 56 plain weave.

*Table 11. Slash test; eight layers polyaramid fabric*

| Variables | Conditions | |
|---|---|---|
| | – | + |
| Conditioning | Dry | Wet |
| Velocity | Low | High |
| Treatment | No | Yes |
| Load (N/lbf) | 18/4 | 45/10 |

| Run | Conditioning | Velocity | Treatment | Load | Number of layers cut |
|---|---|---|---|---|---|
| 1 | – | + | – | – | 1 |
| 2 | + | – | – | – | 1 |
| 3 | – | + | – | – | 2 |
| 4 | – | + | – | – | 2 |
| 5 | – | + | + | – | 1 |
| 6 | + | – | – | – | 1 |
| 7 | – | + | + | – | 1 |
| 8 | – | + | – | – | 1 |
| 9 | – | – | + | – | 4 |
| 10 | + | + | – | – | 3 |
| 11 | – | + | – | – | 4 |
| 12 | – | + | – | – | 3 |
| 13 | – | – | + | + | 3 |
| 14 | + | – | + | + | 3 |
| 15 | – | + | + | + | 4 |
| 16 | + | + | + | + | 4 |

b. Thirty layers of nonwoven UHMWPE in the middle of the sandwich. The woven fabric panels were the same construction as in a.

The test results are presented in table 12.

## V. DISCUSSION

### A. Stab Penetration

The test matrix used in this series of experiments permits the effect of variables, singly and in combination by comparing paired runs. For example, table 1 records the data for eight conditions. In this case, run 1 is the base case; i.e., narrow blade, dry, air backed, impacting perpendicular to the sample.

The base case (run 1) can be compared with run 2 to see the effect of testing while wet; with run 5 to see the effect of impacting at a 45° angle; or run 8 to see the combined effect of testing against a foam backing at an angle of 45° with the sample wet.

*Table 12. Slash test; commercial armor*

Model B (UHMWPE 10-20-10)

| Run | Load | | Velocity | | Number of layers cut |
|---|---|---|---|---|---|
| | (N) | (lbf) | (ms) | (ft/s) | |
| 1 | 45 | 10 | 4.3 | 1.3 | 7 |
| 2 | 69 | 15.5 | 4.2 | 1.3 | 13 |
| 3 | 98 | 22 | 4.1 | 1.2 | 16 |
| 4 | 98 | 22 | 1.6 | .48 | 15 |

Model C (UHMWPE 10-30-10)

| Run | Load | | Velocity | | Number of layers cut |
|---|---|---|---|---|---|
| | (N) | (lbf) | (ms) | (ft/s) | |
| 1 | 98 | 22 | 1.1 | 3.8 | 12 |
| 2 | 98 | 22 | 1.1 | 3.8 | 12 |
| 3 | 45 | 10 | 1.2 | 3.9 | 8 |
| 4 | 69 | 15.5 | 1.2 | 3.9 | 12 |

The discussion that follows is based upon these types of data comparisons.

1. Static

The graphs shown in figure 9 are typical of all static test results: in general the force increases until penetration begins, which results in an immediate reduction in force followed by another force increase as the material again resists penetration. As penetration resumes, the force drops again and the process repeats until all of the material is penetrated or until the blade, under a 62 N (14 lbf) load, is stopped. The force required to start penetration varies from 8 N (1.8 lbf) to 44 N (9.8 lbf).

Table 1 presents the force upon the sample at the start of penetration exerted by the narrow blade as a consequence of three variables (conditioning, backing, and angle) singly, and in combination for 32 layer samples of polyaramid fabric. The average force (each condition was replicated three times) when the sample is wet increases from 16 to 29 N, indicating that the wet polyaramid fabric may be more resistant to penetration than when it is dry. There is also a slight increase in the average force when the air backing is replaced by the foam backing (16 to 20 N). The average force to start penetration decreases from 16 N at an angle of zero, to 8.8 N at an angle of 45°. The combination of a wet sample with a foam backing again demonstrates an increase in force from 16 to 30.6 N. In the case of tests while wet at a 45° angle, the force decreases from 16 to 13.2 N. Tests while dry against the foam backing result in an increase in force from 16 to 18.6 N, while tests when wet against the foam backing at an angle result in a decrease in force from 16 to 12 N.

A comparison of the forces recorded for single variables with those of combinations of variables appear to support the conclusion that the polyaramid fabric is more resistant to initial penetration by the narrow blade when wet, and less resistant to initial penetration at an angle. There is, however, considerable scatter in the data and the results concern only the force required to start penetration.

As discussed earlier, since none of the 32 layer samples were penetrated completely in the static tests, the test sequence was repeated using 24 layer samples of the same material with both narrow and wide test blades. Table 2 presents the force required to penetrate these samples, and the depth of penetration for each test.

During this series of tests, the effects of the backing material and the angle of attack upon the penetration force of the narrow blade were not pronounced; in both cases, the single variable only reduced the penetration force from 49 to 48 N. Tests with the fabric wet, however, resulted in an increase in force from 49 to 57 N; the same was true for the combination of testing wet against a foam backing. The tests while wet at an angle only demonstrated an increase in force of 1 N, while all those variables in combination again resulted in an increase in force of 9 N (49 to 58). It would appear that the polyaramid fabric is more resistant to penetration by the narrow blade while wet. The backing material and angle do not appear to have a major influence on the test results.

The wide blade penetration characteristics were somewhat different than those of the narrow blade. The results of tests with the single variables showed an increase in the force to penetrate the samples of 2 N (42 to 44) while wet; a decease of 2 N (42 to 40) when tested against the foam backing, and an increase of 7 N (42 to 49) when tested at an angle. Tests with the aramid sample wet against the foam backing, showed an increase of 8 N (42 to 50), which is not consistent with the results of single variable testing. Tests conducted with the sample wet at an angle showed an increase in force of 2 N, while tests at an angle against the foam backing showed a decease in force of 1 N. Finally, tests at an angle with the sample wet against the foam backing showed an increase in force of 1 N.

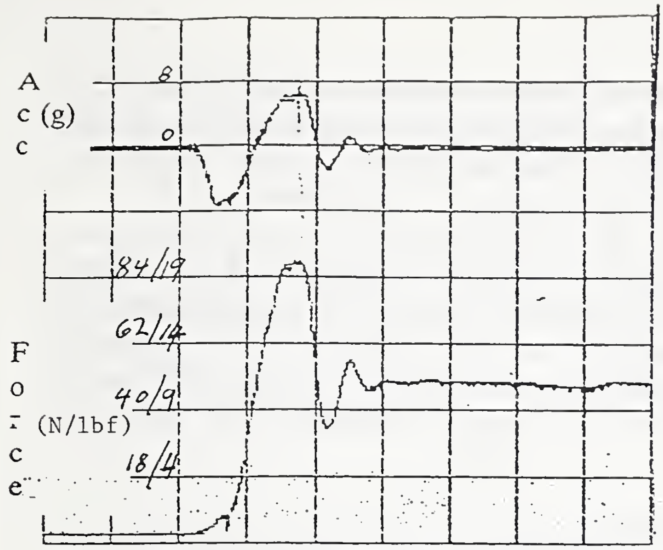
Overall, the data for the static testing of 24 layer polyaramid samples support the general conclusion that the wide blade is generally more of a penetration threat than the narrow blade, and is less sensitive to the variable of conditioning and backing than the narrow blade. The fact that in all cases the wide blade penetrated a greater distance through the sample, provides additional support for the conclusion that the wide blade is more of a penetrator than the narrow blade. While the single variable test at an angle would lead to the conclusion that the wide blade requires more force to penetrate at an angle, this is not the case for any of the other experiments with two or more variables that included tests at an angle. Given the scatter in the data for static tests with 32 layer samples, it is quite possible that none of the variables other than narrow v. wide blade geometry had an appreciable effect upon test results obtained during static tests of 24 layers of polyaramid samples.

2. Dynamic

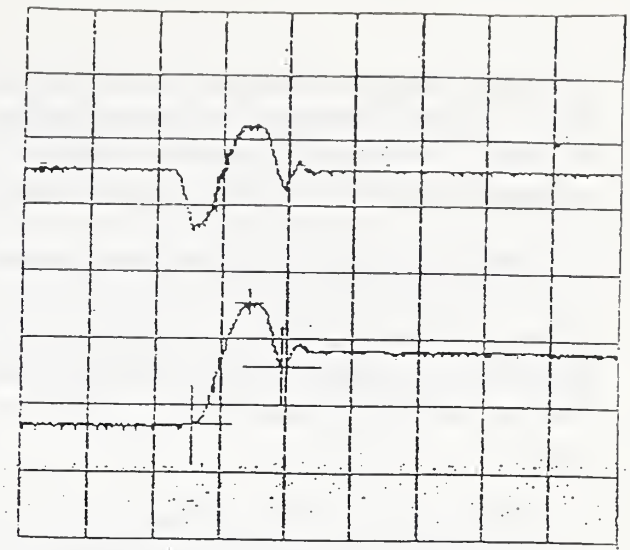
Table 3 presents the results of dynamic tests of 24 layers of polyaramid fabric, in which the blade was released following contact with the sample surface. The graphs shown in figure 10 are typical of all dynamic test results.

As was the case in the static testing, the wide blade consistently required less force to penetrate the sample than the narrow blade for single variable experiments. The wide blade penetration force of 52 N air backed, increased to 53 N when wet, and remained the same when tested with a foam backing (52 N). The penetration force, however, decreased to 45 N when tests were conducted at an angle. Likewise, the force to penetrate at an angle against the foam backing was 45 N. The fact that the penetration force with a wet sample against the foam backing was 53 N (the same as air backed, and the force for wet and dry singly was the same 52 N), would indicate that neither backing nor conditioning influences the results of dynamic tests with the wide blade.

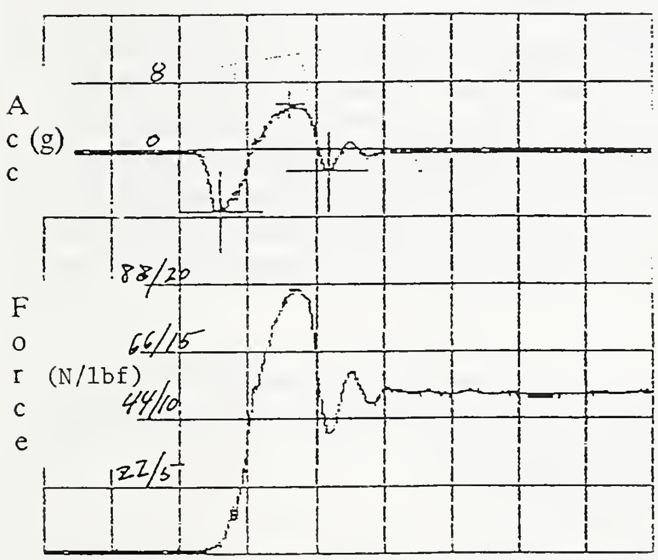
When tested at an angle against the foam backing, the penetration force of 45 N for the wide blade was the same as that of the single variable angle test. In the case of the



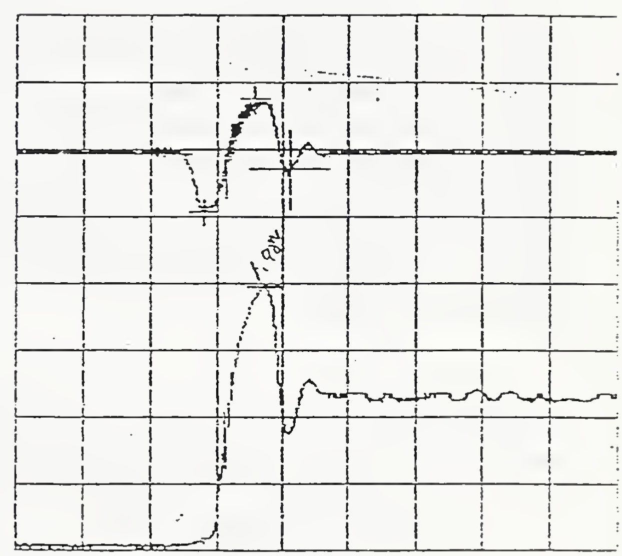

a. Dry conditioning
Air backing
45° impact




b. Dry conditioning
Polyethylene backing
0° impact




c. Wet conditioning
Polyethylene backing
45° impact




d. Wet conditioning
Polyethylene backing
0° impact

*Figure 10. Dynamic stab penetration test; twenty-four layers polyaramid fabric. Dagger style machined blade; free fall; height = 0.*

combined variables of tests at an angle with the sample wet, the force increased from 52 to 60 N. In tests at an angle while wet against the foam backing, the force decreases from 52 to 49 N. This would appear to indicate that the conditioning has a greater effect than observed in the single variable conditioning test.

The tests with the narrow blade showed a decrease in penetration force from 61 to 53 and 58 N respectively for the single variable of backing and angle. The data point for the single variable of conditioning (98 N) is excluded from analysis. Given the 8 N decrease in force for the single variable tests while wet, and the modest increase from 61 to 63 while wet on the foam backing, one might conclude that the conditioning does effect the penetration resistance.

The reduction in force from 61 to 55 and 53 N respectively for tests at an angle while wet, and tests while dry at an angle against the foam backing again support the effect of the angle, as does the reduction in force from 61 to 55 N for tests at an angle while wet against the foam backing.

Table 4 presents the results of dynamic tests of 40 layer polyaramid fabric samples. As was the case for tests of 24 layer samples of the same material, the wide blade requires less force to penetrate the samples than the narrow blade (116 v. 98 N), dry with an air backing, the penetration force for the wide blade was the same for air backing and foam backing, however, the force required for the narrow blade decreased 26 N (116 to 80) when tested against backing at a 45° angle with air backing, the force required to penetrate the sample increased for both blades, 18 N for the narrow blade and 31 N for the wide blade. Tests against the foam backing at a 45° angle support the conclusion that the narrow blade force required to penetrate the sample is effected by the backing and impact angle (foam backing decreased the force by 36 N, impact at an angle air backed increases the force by 18 N, and tests against the foam backing at a 45° angle result in a force of 111 N, an increase of 31 N).

The force required for the wide blade to penetrate the sample increased by 31 N when impacted at a 45° angle using the foam backing. In all cases, the depth of penetration was less than that experienced in tests of 24 layer polyaramid fabric.

3. Commercial Blades

Results of tests with commercial blades against 40 layers of polyaramid fabric are presented in tables 5 and 6.

For the hunting style blade, a drop height of 15 cm (6 in) was required to penetrate 40 layers of polyaramid fabric (see table 5). This represents an impact energy of 10 J (7 ft-lbs).

For the Tanto style blade, there were no penetrations using drop heights up to 38 cm (15 in). This represents an impact energy of 24 J (18 ft-lbs); see table 6.

The narrow blade, wide blade, and awl were tested against 24 and 40 layers of polyaramid fabric by lowering the penetrators until they touched the front surface of the sample then allowing them to fall under the weight of the carriage. The results are summarized in table 13.

In both series of tests, the wide blade penetrated most and required the least force while the awl penetrated least.

*Table 13. Comparison of armor resistance to dynamic penetration using various blade geometries; polyaramid fabric; polyethylene backing; free fall; height = 0*

Twenty-four layers

| | Penetration depth* | | Force to penetrate | |
|---|---|---|---|---|
| | (cm) | (in) | (N) | (lbf) |
| Narrow blade | 2.5 | 1 | 93 | 21 |
| Wide blade | 6.7 | 2 5/8 | 85 | 19 |
| Awl | 1.6 | 5/8 | 125 | 28 |

Forty layers

| | Penetration depth* | | Force to penetrate | |
|---|---|---|---|---|
| | (cm) | (in) | (N) | (lbf) |
| Narrow blade | 2.2 | 7/8 | 103 | 23 |
| Wide blade | 2.9 | 1 1/8 | 89 | 20 |
| Awl | 0.3 | 1/8 | 96 | 21.5 |

*Length of blade exiting back surface.

4. Commercial Armor

The results of stab penetration tests conducted on commercial armor are shown in table 7.

Only two samples, those constructed with titanium plates, defeated the blade. It should be noted that an impact energy of 1.6 J (1.2 ft-lbs) or less resulted in complete penetration of polyaramid and UHMWPE armor while the titanium, armors withstood an impact energy of 13 J (9.3 ft-lbs).

Testing with machined steel blades was terminated because the blades were damaged on impact with titanium armor. Additional tests on hard armor were conducted with a variety of commercial awls. A 39 mm (5/32 in) diameter tungsten carbide awl with a 25° tip angle penetrated the hard armor when dropped from 1.2 m (3.9 ft) [impact energy 74 J (55 ft-lbs)] but would not penetrate soft armor under the same conditions. Instead of penetrating, the awl pressed the armor into the foamed polyethylene backing. Attempts to use sharper awls (5° tip angle) were terminated since the awls would bend or break upon impact with hard armor but would penetrate soft armor.

**B. Slash Penetration**

Table 14 organizes the data in table 8 (eight layer polyaramid fabric samples) in a manner that permits direct comparison of the test results (i.e., layers cut) for static and dynamic tests with two different backing materials for two slashing velocities with samples in the dry and wet condition. At a nominal velocity of 0.45 m/s, the results are comparable, with two or three layers cut on the hard backing and only one on the soft backing in both sets of tests. One half of the test samples were waterproofed, and are identified with an asterisk. At a slash velocity of 0.45 m/s, wet conditioning does not appear to effect the test results.

When the slash velocity is increased to 1.5 m/s, the number of layers cut increases for both the static and dynamic modes; clearly, the slicing velocity has a significant influence on the number of layers that are cut. Again, in both modes, the use of the hard backing results in more layers being cut. An examination of the layers cut shows that two layers dry are cut on the soft backing static, while three are cut with the sample wet; however, the sample was waterproofed. The waterproofed sample (dry) was cut to a depth of three layers on the soft backing during dynamic mode testing, while the nonwaterproofed sample (wet) was cut to a depth of five layers. One could interpret this to mean that wet testing results in a greater depth of slash regardless of waterproofing.

Table 15 organizes the $2^5$ test matrix results presented in table 9 (four layer polyaramid fabric samples) in a manner that allows direct comparison of the static and dynamic test results for two backing materials, two slash velocities, dry and wet samples, and treated or not treated samples.

*Table 14. Slash test; eight layers of polyaramid fabric; $2^{5-1}$ design*

| Slice velocity (m/s) | Conditions | Number of layers cut | | | |
|---|---|---|---|---|---|
| | | Static mode | | Dynamic mode | |
| | | Backing | | Backing | |
| | | Hard | Soft | Hard | Soft |
| 0.45 | Dry | 2 | 1* | 3* | 1 |
| 0.45 | Wet | 3* | 1 | 3 | 1 |
| 1.5 | Dry | 5* | 2 | 8 | 3* |
| 1.5 | Wet | 5* | 3* | 8 | 5* |

*Sample constructed from waterproofed fabric.

*Table 15. Slash test; four layers polyaramid fabric; $2^5$ design*

| Slice velocity (m/s) | Conditions | Number of layers cut | | | |
|---|---|---|---|---|---|
| | | Static mode | | Dynamic mode | |
| | | Backing | | Backing | |
| | | Hard | Soft | Hard | Soft |
| 0.51 | Dry | 4 | 2 | 4 | 1 |
| 0.51 | Wet | 4 | 4 | 4 | 0 |
| 0.45 | Dry, treated | 4 | 0 | 4 | 0 |
| 0.45 | Wet, treated | 4 | 2 | 4 | 1 |
| 1.4 | Dry | 4 | 2 | 4 | 0 |
| 1.4 | Wet | 4 | 4 | 4 | 3 |
| 1.4 | Dry, treated | 4 | 2 | 4 | 2 |
| 1.4 | Wet, treated | 4 | 2 | 4 | 2 |

In all cases, the samples tested on the hard backing, in both test modes, were cut through, so analysis is limited to the results on the soft backing at nominal velocities of 0.5 m/s, the static mode is a more severe test than the dynamic. During this test series, unlike that conducted with eight layer samples, the 1.5 m/s velocity did not appear to have a major influence on the number of layers cut in the static mode. The velocity did, however, appear to have an influence on the results of the dynamic tests. This is due, in part, to the fact that the blade bounces when it first hits the foam backing, so that it is in contact with the sample for a shorter period of time than it is during the static tests.

Based upon the comparison of layers cut for both test modes when dry and wet, it is possible that more layers are cut when nonwaterproofed samples are tested, and that waterproofing does influence the test results when samples are wet.

Table 16 organizes the data from table 10 for tests of eight layers of polyaramid fabric, using only the hard backing, to permit a comparison of static and dynamic modes, slicing velocity, wet and dry, and treated or not treated samples.

In all cases, the samples were cut completely through regardless of condition or slicing velocity in the dynamic test mode. In the first eight layer dynamic test there was a large difference in the number of layers cut based on slash velocity. The static tests, however, appear to demonstrate more layers being cut at 1.4 m/s than at 0.45 m/s.

As with the previous tests, the tests in the static mode with the samples wet result in more layers being cut whether the sample is waterproofed or not.

*Table 16. Slash test; eight layers polyaramid fabric; hard backing*

| Slice velocity (m/s) | Conditions | Number of layers cut | |
|---|---|---|---|
| | | Static | Dynamic |
| 0.57 | Dry | 2 | 8 |
| 0.57 | Wet | 3 | 8 |
| 0.54 | Dry, treated | 3 | 8 |
| 0.54 | Wet, treated | 2 | 8 |
| 1.4 | Dry | 3 | 8 |
| 1.4 | Wet | 8 | 8 |
| 1.4 | Dry, treated | 3 | 8 |
| 1.4 | Wet, treated | 8 | 8 |

Table 17 organizes the test results from table 11 in a manner that permits a comparison of experiments with additional static loads of 7.8 and 44.5 N using eight layer polyaramid samples with a hard backing. As with the other experiments, higher slicing velocities tend to result in an increase in the number of layers cut, and more layers are cut with the 45 N additional load than the 17 N additional loading. The variables of wet and dry conditioning and fabric treatments do not appear to have a significant effect on the results.

Results of slash penetration tests with commercial armor are presented in table 12. As in earlier tests, blade velocity did not appear to affect penetration but load had a measurable effect on results.

*Table 17. Slash test; eight layers polyaramid fabric; varying load on blade*

| Slice Velocity (m/s) | Condition | Number of layers cut | |
|---|---|---|---|
| | | 18 N Load | 45 N Load |
| 0.45 | Dry | 1 | 3 |
| 0.45 | Wet | 1 | 3 |
| 0.45 | Treated | 1 | 3 |
| 0.45 | Wet, treated | 1 | 3 |
| 1.4 | Dry | 2 | 4 |
| 1.4 | Wet | 2 | 3 |
| 1.4 | Treated | 1 | 4 |
| 1.4 | Wet, treated | 1 | 4 |

# VI. CONCLUSIONS

## A. Stab Penetration

The most significant parameter is blade geometry. Soft armor offers virtually no protection against dagger-type machined blades but is difficult to penetrate with blades that have other shapes. An awl with 39 mm (5/32 in) diameter and 5° tip angle penetrated soft armor with approximately the same applied energy as machined blades.

Unfortunately, penetrators that are most effective against soft armor are damaged by hard armor while those that are capable of penetrating hard armor will not penetrate soft armor. It is recommended that the 5° commercial awl be used as a standard penetrator since it approximates the threat of the machined blades and is expendable because of its low cost (about $1 each) compared to machined blades (about $500 each).

Since results are apparently not affected by backing material, impact angle, or conditioning, it is recommended that for expediency, penetration tests be conducted with dry samples, foamed polyethylene backing, and 0° impact angle.

### B. Slash Penetration

Penetration by slicing is a strong function of backing material and greatest penetration occurs when the blade is dropped onto a sample mounted on hard backing.

Waterproofed fabric did not appear to influence the results; however, more layers are cut at a higher slash velocity, and there may be a tendency toward more layers being cut when the sample is wet.

Additional static loadings of 18 N (4 lbf) and 45 N (10 lbf) resulted in cutting about the same number of layers as with an unloaded blade.

An apparent anomaly was the reduced penetration when the blade was dropped onto soft-backed armor as opposed to the blade resting on the sample. This was the reverse of the more predictable results obtained with the hard-backed armor.

When the armor is mounted on soft backing the blade bounces immediately after impact while the armor continues to move under the blade without contact. Thus, actual contact time (slicing time) between blade and armor is greatly reduced. There is less bounce with hard backing and initial penetration is also greater.

## VII. FUTURE WORK

Additional tests will be done to correlate penetration of the awl with machined blades. These tests will be conducted on a universal testing machine which produces constant displacement at rates ranging from 0.50 to 500 mm (0.02 to 20 in) per minute. Force is read continuously on strip chart recorder.

Penetration tests also will be conducted with a hydraulic, constant acceleration system. Blades will be propelled at accelerations between 0 and 4.6 m/s$^2$ (15 ft/s$^2$). Force will be monitored with a force transducer during penetration.