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

EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

FINAL REPORT

PROTECTIVE ARMOR DEVELOPMENT PROGRAM

Volume III - Appendices

DEVELOPMENT

Prepared for

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

The Aerospace Corporation

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Law Enforcement Development Group
THE AEROSPACE CORPORATION
El Segundo, California

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Prepared for

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Approved

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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 are less than half the weight 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.

The Technical Discussion, Volume II, 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.

This volume, Volume III--Appendices, contains some of the backup material used in the Technical Discussion. Although some of the appendices included in this volume have been published previously, they have also been included herein in the interests of completeness and ease of reference.

APPENDIX A

BALLISTIC INTERACTION PHENOMENOLOGY STUDY

BALLISTIC INTERACTION PHENOMENOLOGY STUDY

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CHAPTER I. INTRODUCTION

The objective of the Ballistic Interaction Phenomenology Program is to gain a better physical understanding of the roles of bullet, soft armor, and backing material during a ballistic encounter. Through the understanding of the phenomenological behavior of soft armor under bullet impact, optimization of fabric parameters and improvements in soft armor design will be more readily achieved, and analytical modeling of the process more realistically carried out.

Following a preliminary review by an ad hoc committee comprised of personnel from The Aerospace Corporation Materials Sciences Laboratory, an experimental program was outlined and used as a guide during this study. While a major goal of the LEAA Protective Body Armor Development Program is to optimize parameters that prevent bullet penetration of armor, it is also recognized that blunt trauma effects on the wearer must be minimized. Hence, there is an interest in minimizing the local momentum and energy transfer to living tissue (the backing material) through an understanding of parameters affecting the momentum and energy distribution between bullet, soft armor, and backing material.

Ballistic testing performed by the Land Warfare Laboratory (LWL) together with supplementary testing by Aerospace has shown that three plies of simply woven, 400-denier Kevlar 29 yarn defeats a 158-grain .38 Special round-nose bullet traveling at 800 ft/sec. Additional testing showed that seven plies of the same fabric were required to defeat the "less lethal"

40-grain .22 caliber bullet at 1000 ft/sec. By comparing these two threats in usual ballistic terms, such as kinetic energy and sectional density, we find the .38 Special to be superior in almost every case; the only exception is the kinetic energy per cross-sectional area, which is about 5% higher for the .22 caliber. This result implies that different physical mechanisms are influencing the interaction, depending upon the bullet's configuration and velocity.

The impacting bullet possesses both kinetic energy ($1/2\ mv^2$) and momentum (mv) because of its mass m and velocity v. Thus, a 158-grain bullet traveling at 800 ft/sec has 0.55 lb sec of momentum and 224 ft lb of energy. The bullet has some additional kinetic energy and momentum because of its rotational velocity and inertia. A .38 Special bullet with a rotation rate of 1 rev/ft (standard barrel twist) has 0.025 ft lb and 6.4×10^{-5} lb sec of angular kinetic energy and momentum, respectively; this is obviously negligible relative to the energy and momentum resulting from its linear motion.

Upon impact, all the momentum is transferred to the armor and backing material. The momentum is conserved in the interaction; however, nearly all the kinetic energy is dissipated in the form of work through three basic mechanisms, i.e., deformation of the backing material, deflection and deformation of the fabric and fiber breakage, and deformation of the bullet. The distribution of the absorbed energy is determined by the response of all three variables. For example, when a fabric with enough plies to prevent complete penetration is held in a suitable frame with only air as a backing, upon impact, a negligible amount of energy is absorbed in displacing the air, even though large displacement of the fabric occurs. This implies that virtually all the energy is dissipated in the deformation of the fabric and bullet. A more viscous backing material, such as gelatin or clay, will absorb a significant portion of the impact energy by being displaced. Consequently, the fabric is strained to a lesser degree and will absorb less energy. A comparatively rigid backing, such as wood or bone, would probably result in almost all the energy being dissipated in the backing and bullet, since the fabric will hardly be deformed at all.

The dependence of the energy transfer on properties of the soft armor and bullet can be realized by first considering a very loosely woven fabric, i.e., one through which a .38-caliber bullet can easily pass without intercepting any yarns. Here, energy absorbed by the armor will be zero; i.e., all the kinetic energy will be dissipated in bullet deformation and penetration of the backing material. Now, as the weave configuration is progressively tightened, the .38-caliber bullet will eventually be defeated by the armor. However, a smaller diameter bullet, such as a .22 caliber, will still find holes in the weave through which it can easily penetrate. This explains the apparent anomaly in which seven plies of fabric were required to defeat the .22-caliber bullet when only three plies were required for the .38-caliber bullet. Thus, before studying the overall interaction between bullet, armor, and backing, we must identify the critical parameters influencing the behavior of each subsystem.

A. Bullet Behavior

The parameters influencing momentum and energy transfer between bullet and target are velocity, caliber, mass, shape or profile, and hardness (including jacketing). The energy and momentum of the bullet can be easily calculated given its mass and velocity. For a bullet of fixed mass and velocity, the forces exerted on the target depend essentially on diameter. Thus, the flat-nose wad cutter intercepts many yarns upon impact with the armor, thereby distributing the forces over a large area. Consequently, relatively low pressures are exerted on the yarns, and the armor easily defeats this bullet. In the case of the round-nose soft-lead bullet, the pressures directly beneath the nose are relatively high. However, because of the soft lead, the bullet easily mushrooms and spreads the forces over a larger area, resulting in both lower pressures and loading of additional yarns. With fully jacketed bullets like the 9-mm bullet, expansion is inhibited by the hard copper or steel jacket. Armor loading is localized, resulting in high pressures. Penetration occurs from failure of the yarns directly under the impact and a pushing aside of adjacent yarns.

The ballistic threat was established to be a .38-caliber 158-grain round-nose lead bullet at 800 ft/sec. Although the .22-caliber bullet at 1000 ft/sec poses a higher threat from a penetration standpoint, its low kinetic energy and momentum result in negligible blunt trauma. The .22-caliber bullet, therefore, was not included in the laboratory phenomenology study. In order to determine the portion of the total kinetic energy absorbed in deforming the bullet, several bullets were mounted in the Instron testing machine and deformed to approximately the same shape as would result from a ballistic impact with the soft armor having gelatin or clay backing. Between 10 and 20 ft lb of energy were required for the quasi-static deformation, or between 5 and 10% of the total energy.

B. Soft-Armor Behavior

DuPont's Kevlar 29 is a highly oriented, linear, aromatic polyamide fiber with a Young's modulus of $\sim 9.0 \times 10^6$ psi, 3 to 4% strain to failure, and an ultimate strength of $\sim 0.4 \times 10^6$ psi, which makes it one of the strongest synthetic fibers presently available. This material is available in various sizes of yarns, i.e., 200, 400, and 1000 denier, which can be woven into any standard configuration. Because of the rather complex configuration of a woven fabric, additional variables are introduced in describing fabric behavior.

The fabric essentially acts as a net in preventing penetration of the bullet, i.e., the fabric must catch the bullet in order to stop it. The fabric parameters influencing this mechanism are yarn configuration, tightness or density of weave, yarn diameter or denier, yarn twist, and the frictional characteristics of the yarn. The optimum ballistic fabric would consist of the lowest denier, untwisted yarn in the tightest, simple weave, i.e., one over-one under, possible with no lubricants present, for the following reasons: (1) the tighter, simple weave is the most effective in spreading the load to adjacent fibers since each yarn is in close contact with the yarns running normal to it; (2) since bullet penetration is effected through yarn separation, the smaller denier, untwisted yarns result in smaller holes being formed at the crossover points; (3) the presence of lubricants on the yarns aid in yarn separation; and (4) once penetration by slipping of the bullet through the weave is prevented, bullet penetration must be accompanied with fiber failure, which absorbs considerably more of the bullet's energy than the slipping-through process.

The above hypothesis was verified experimentally by ballistically testing a 200-denier, simple-weave fabric with 90 × 110 pics/in. Six plies of the fabric defeated both the .38- and .22-caliber bullets at 800 and 1000 ft/sec, respectively. Furthermore, the .22-caliber bullet mushroomed and bounced off the first ply in the same manner as did the .38-caliber bullet, indicating similar interaction mechanisms (the .22-caliber bullet always penetrates numerous plies of the 400- and 1000-denier fabrics).

The response of the woven fabric to an applied load differs markedly from the response of a single yarn. A single yarn of Kevlar 29 exhibits a nearly linear stress-strain behavior to failure, i.e., the stretch or strain is directly proportional to the applied load. However, the stress-strain response of the fabric is extremely nonlinear. Nonlinear behavior results from the initial crimp (the looping over and under of yarns normal to the direction of pull) existing in the yarns because of the woven configuration. Initial loading of the fabric is accompanied by high elongation in the direction of pull as the crimp is removed. Eventually, the high stiffness of the Kevlar 29 fibers respond directly, and the stress-strain response finally becomes linear. As a result of the woven configuration, the ultimate elongation for the fabric is 6 to 8%, or 100% greater than that of the yarn.

The uncrimping mechanism also depends upon the orientation of the fabric, e.g., warp, fill, and bias relative to the direction of the applied load. Materials that exhibit angular-dependent behavior are designated anisotropic and require more extensive measurements to characterize their behavior. Once the material is fully characterized, material response can be predicted under any arbitrary loading condition. Accordingly, a critical step in the present study has been the characterization of the material and the development of an analytical expression for the anisotropic stress-strain behavior on the basis of experimental data. The base-line material used for the study was the 400-denier, double-twist, 36 × 36 pics/in. Kevlar 29 yarn, hereafter referred to as 400/2 (36 × 36). Later, limited experimentation was carried out with 1000-denier, single-twist, 31 × 31 pics/in. Kevlar 29 yarn, 1000/1 (31 × 31).

Theoretically, once the response of the fabric is characterized, it is possible to predict the behavior of the fabric under any loading conditions, e.g., ballistic impact. Unfortunately, the solution for this problem does not exist. The standard engineering approach under these circumstances is to test the material under loading conditions consistent with the desired use. This would imply ballistic testing. Although ballistic testing enables qualitative measurements of relative superiority between various fabrics, such testing does not allow measurements of the forces involved. At best, high-speed photography allows determination of displacement with time. However, as previously discussed, the kinetic energy (the product of force and displacement) and momentum (the product of force and time) determine the behavior of bullet, armor, and backing material under impact. It, therefore, becomes advantageous to select intermediate steps between uniaxial fabric behavior and ballistic impact.

Two laboratory tests were designed to fulfill this need: the static indentor and pendulum impact tests. A 10-in.-diameter cylindrical fixture was constructed that allowed the Kevlar 29 fabric to be held and clamped like a drum head. This fixture was used for two types of tests: (1) The static indentor test was performed by placing the indentor fixture on the Instron testing machine. A bullet-shaped steel indentor was used to load the clamped fabric. Thus, a static ballistic test could be performed in the laboratory. Both displacement and force, and, therefore, energy, were continuously recorded up to failure. (2) The pendulum impact test was performed by mounting the indentor fixture on a pendulum impact tester with a bullet-shaped steel indentor mounted to the pendulum. Strain gauges mounted on the indentor allowed continuous measurement of force and time, and, consequently, momentum, on an oscilloscope. Proper integration of this information additionally yields velocity and displacement with time, and, hence, force versus displacement.

These tests allowed quantative experiments to be conducted in which the effect of ply number, kinetic energy, and momentum could be studied. In addition, various backing materials, i.e., air, gelatin, and clay, could be used behind the armor. The dynamic laboratory tests are not intended to simulate directly bullet impact conditions, but they provide unique instrumented data in an intermediate loading rate range, which has been useful in extrapolating response under ballistic loading and which will provide an experimental data bank for verifying analytical prediction techniques as they are developed.

A limited number of biaxial tests were carried out to provide the necessary information for checking the analytical expression, generated from uniaxial tests, describing the anisotropic behavior of the Kevlar 29. Unfortunately, problems in clamping the fabric arose that were not solved because of the program time schedule.

C. Backing Material Behavior

The human body constitutes extremely complex material. In general, biological materials are multiphase, nonhomogeneous, anisotropic, and nonlinear. An understanding of the ballistic interaction necessitates an understanding of the backing material in addition to bullet and soft armor. Since this phenomenology study was directed toward an understanding of the soft armor, it becomes advantageous to eliminate as many unknown variables as possible. The approach is to choose simple backing materials with known properties that represent the extremes of the human body.

Two such materials are gelatin and oil-base modeling clay. Gelatin, a highly elastic material, exhibits nearly total recovery to a deformation. Gelatin has been used successfully for studying both ballistic penetration and blunt trauma in living tissue. A major advantage of gelatin is its translucence, which allows high-speed photography to be used for studying the ballistic process. Conversely, clay, a highly plastic material, undergoes viscous flow when deformed and exhibits very little recovery capability, and, as a result, the use of clay allows analysis of the cavities formed during impact. The use of these two materials allows the response of the human body to be bracketed for most parts of the body; bone, such as the rib cage, would obviously fall outside these brackets.

CHAPTER II. MATERIAL CHARACTERIZATION

In order to describe the mechanical behavior of a material, it is necessary to know the relationship between applied load (stress) and the corresponding material deformation (strain), not only in the direction of loading but also in the direction transverse to the direction of loading. Common engineering materials, such as steel, exhibit a linear, uniaxial stress-strain curve up to the point where the material begins to fail (yield). The slope of the linear portion of the stress-strain curve is the so-called elastic modulus or Young's modulus for the material and is a measure of the stiffness of the material. Homogeneous materials tend to resist volume change; stretching in one direction is generally accompanied by contractions of the material in directions perpendicular to the pull direction. The relation between lateral strain and longitudinal strain is given by Poisson's ratio for the material.

Most common engineering materials can be assumed to be isotropic, i.e., they are fully characterized by measurements in uniaxial tension in any arbitrary direction in the material. Fabrics, because of their woven configuration, are neither homogeneous nor isotropic. Their mechanical behavior depends on the orientation of the applied stresses or strains relative to their primary weaving directions, generally known as the warp and fill directions. Measurements must be made in several directions and under different stress fields in order to be able to predict fabric response under an arbitrary loading.

Three quasi-static test methods were used to study the mechanical behavior of the Kevlar 29 fabric. These were uniaxial tension in the fill, 15-, 30-, and 45-deg off-fill, and warp directions; nearly uniform biaxial tension, achieved by applying hydrostatic pressure over the fabric while held in a membrane configuration; and biaxial tension in which the geometry of the ballistic interaction is simulated by a steel indentor.

A. Uniaxial Tension

The uniaxial tension test provides the most fundamental data on material behavior and, in principle, is the simplest to perform and evaluate. In practice, considerable care must be exercised, particularly in regard to the manner in which the test specimen is held in the testing machine grips.

Single-ply test specimens were cut 2 in. wide by 10 in. long; five different cloth orientations were used. These were the fill; 15-, 30-, and 45-deg off-fill; and the 90-deg (warp) off-fill direction. In order to eliminate slippage in the jaws, 2-in.-square cardboard tabs were glued to the ends of the specimens with 3M brand contact cement. For measurement of longitudinal and lateral strains, a rectangular grid was inked on the central portion of the specimen. Figure 1 is a photograph of a specimen oriented 15-deg off fill, mounted in the grip. Photographs were taken of the speciment at regular load intervals as the specimen was pulled in a standard Instron testing machine at a rate of 0.5 in./in./min. Photographs were indexed to the load, which was recorded on a strip chart recorder.

The Blatz, Scharda, and Tschoegl (BST) strain energy function was chosen to represent the behavior of the Kevlar 29 fabric because of its

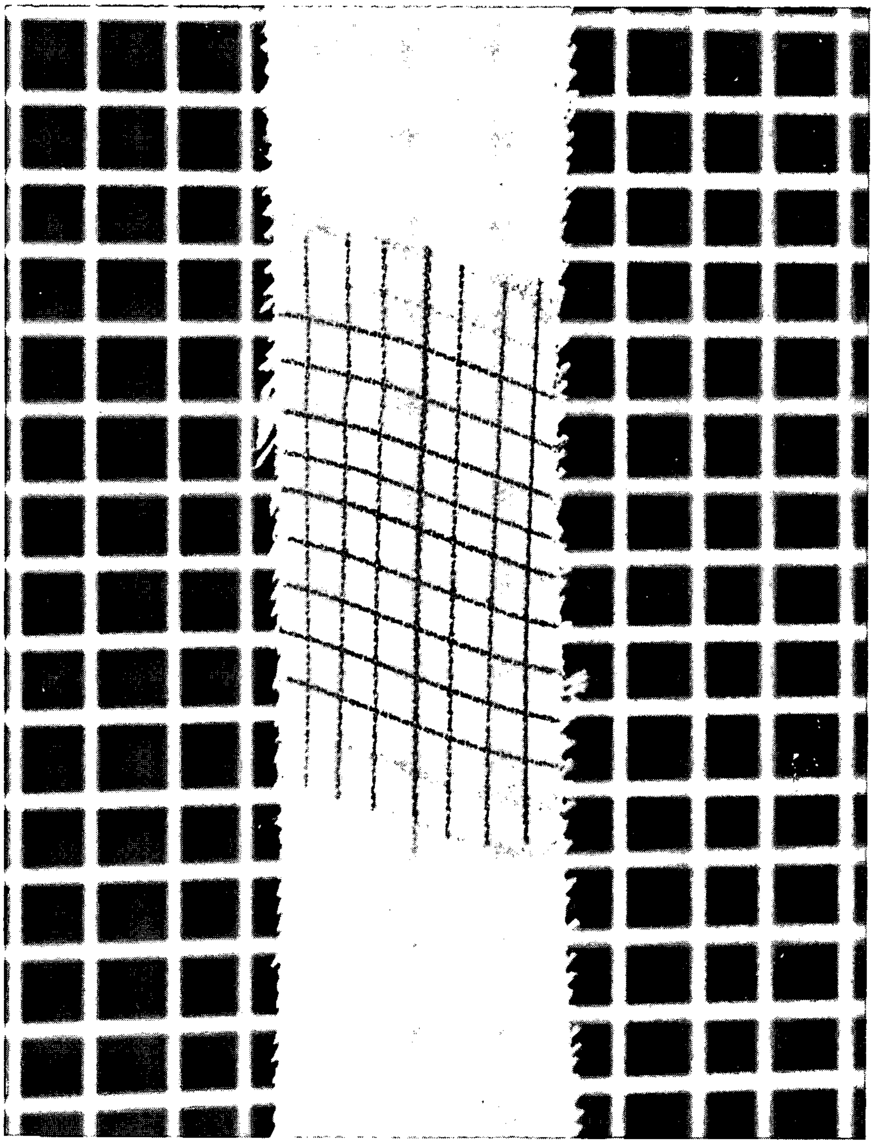


Fig. 1. Tensile Specimen Oriented 15-deg Off Fill, Mounted in Grip

success in describing materials exhibiting highly nonlinear stress-strain responses.[1] The parameters of this strain energy function W are defined as the stretch of the principal stress triad relative to a fixed Cartesian system imbedded with one axis parallel to the fill direction ($\theta = 0$). This function takes the form

$$W = \frac{2G}{n}\left[\sum \frac{\lambda_\alpha^n - 1}{n} + \frac{1 - 2\nu}{n\nu}\left(\mathscr{J}^{-\frac{n\nu}{1-2\nu}} - 1\right)\right] \tag{1}$$

where

G is the shear modulus of the material

n is the BST exponent

λ_α is a principal stretch ratio, α = 1, 2, 3

ν is Poisson's ratio

$\mathscr{J}$ is the volumetric stretch ratio

At present, G, n, and ν are functions of the angle θ, where $f(\theta)$ is yet to be defined. In the succeeding section, we will demonstrate the success of Eq. (1) in describing the available uniaxial data and define the angular dependence of Young's modulus, which is linearly related to the shear modulus. This function will be completely determined from the uniaxial data and be the analytic representation of the constitutive behavior of the Kevlar 29 fabric.

[1] P. Blatz, S. Sharda, and N. Tschoegl, "Strain energy function for rubber-like material based on generalized measure of strain," Transactions of the Society of Rheology, Vol. 18, No. 1, 1974, p. 145.

Consequently, it can be incorporated into an armor impact model, which can be used to predict the pendulum force indentation and energy-volume-depth measurements.

The so-called principal Piola stress or, simply, load is obtained from Eq. (1) in the form

$$\sigma_\alpha = \frac{\partial W}{\partial \lambda_\alpha} = \frac{2G}{n}\left[\lambda^{n-1} - \frac{J^{-\frac{n\nu}{1-2\nu}}}{\lambda_\alpha}\right] \tag{2}$$

For the case of simple tension, we have

$$\lambda_1 = \lambda \qquad \sigma_1 = \sigma \tag{3}$$

$$\lambda_2 = \lambda_3 = \sqrt{\frac{J}{\lambda}} \qquad \sigma_2 = \sigma_3 = 0 \tag{4}$$

so that

$$\sigma\lambda = \frac{2G}{n}\left[\lambda^n - \lambda^{-n\nu}\right] \tag{5}$$

and

$$J = \lambda^{1-2\nu} \tag{6}$$

Since the maximum strain occurring in uniaxial tension (for the Kevlar 29) does not exceed 10%, we can approximate Eq. (5) by

$$\sigma\lambda = E \ln\lambda\left[1 + \frac{n(1-\nu)}{2}\ln\lambda\right] \tag{7}$$

where the shear modulus has been replaced by Young's modulus. We now use the data to determine the parameters in Eqs. (6) and (7).

Figure 2 is a plot of $\sigma\lambda$ versus ln λ for two cases: $\theta = 0$ deg (fill) and $\theta = 45$ deg. For $\theta = 0$ deg (fill), the behavior is linear up to 4% strain, beyond which failure ensued. In the 45-deg case, nonlinearity ensues at 2% strain. Figure 3 is for the $\theta = 15$-deg case, with nonlinearity again setting in beyond 2% strain. Figure 4 is for the 90-deg case (warp) with nonlinearity occurring beyond 2% strain. In each of the four cases, the initial slope (Young's Modulus E) of the stress-strain curve was measured and is plotted versus sin θ in Fig. 5. We find that the angular correlation can be represented by

$$E = E_0 + (E_1 - E_0) \sin\theta \quad (8)$$

where E_0 = 70, 000 psi and E_1 = 400, 000 psi.

The lateral elongation is plotted versus the longitudinal elongation in Fig. 6 for the 0-, 30-, 45-, and 90-deg (warp) cases. An excellent linear correlation is demonstrated in the log-log plot and corresponds to Poisson's ratio of 3. 5, 4. 2, and 2. 8, respectively, which implies that the fill fibers contract highly when the specimen is stretched in the off-fill directions. Since the largest value theoretically possible for Poisson's ratio is one-half for homogeneous materials; these values emphasize the fact that the fabric is not homogeneous, but rather contains voids and irregularities. Note that the observed behavior and values are properties of the fabric composite and not of a single strand of yarn. A more thorough analysis of this situation should include hysteresis, which implies that some kind of damage function

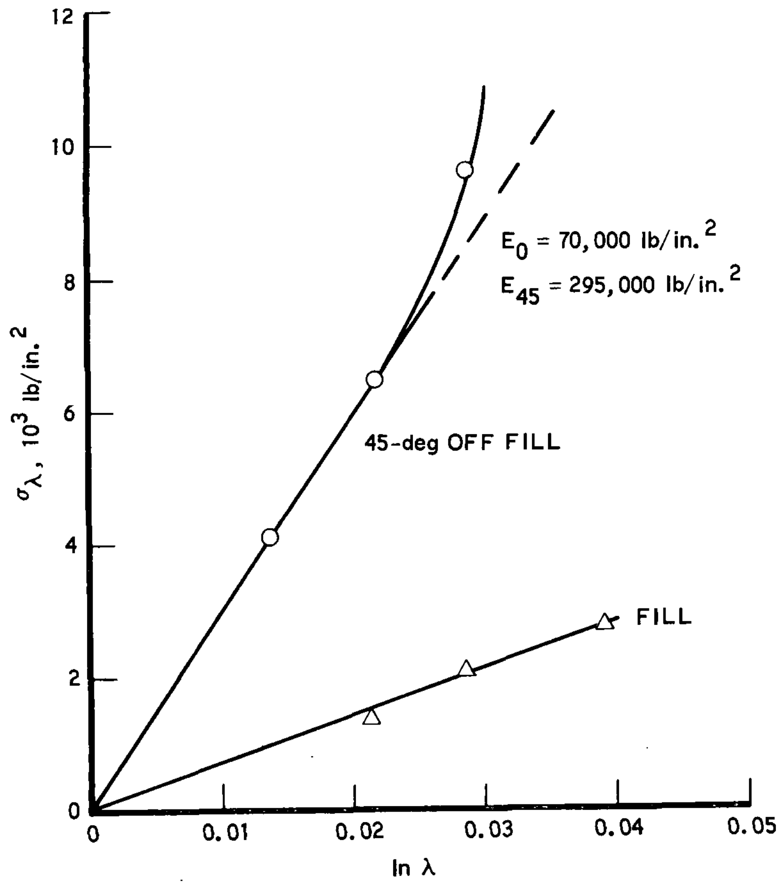


Fig. 2. $\sigma\lambda$ vs $\ln\lambda$ for Fill and 45-deg Off Fill

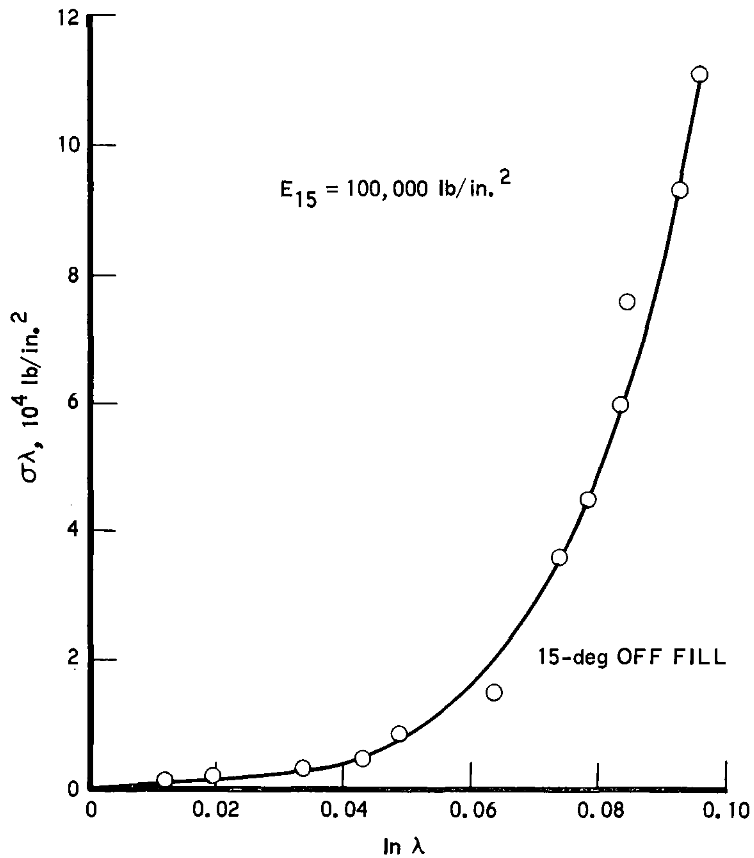


Fig. 3. $\sigma\lambda$ vs $\ln\lambda$ for 15-deg Off Fill

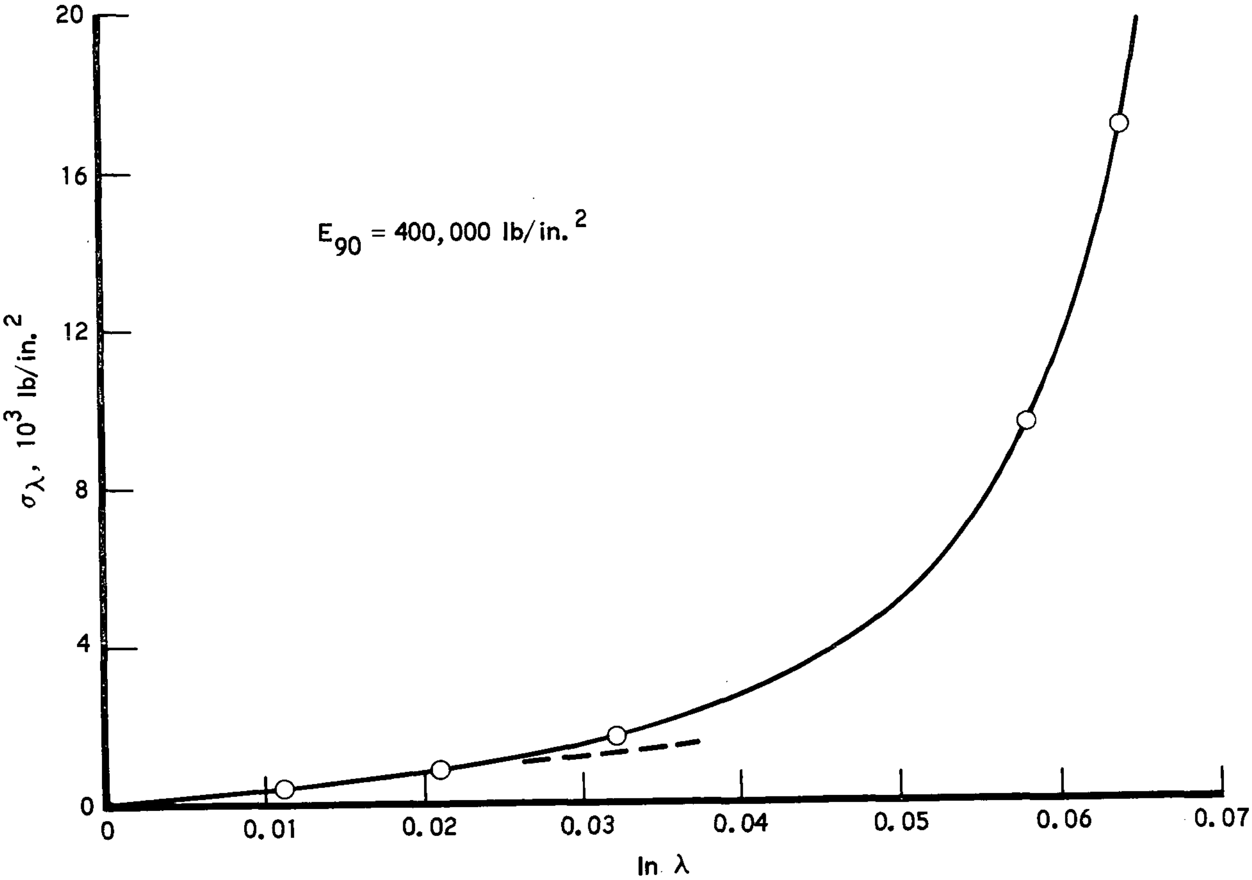


Fig. 4. $\sigma\lambda$ vs ln λ for 90-deg Off Fill (Warp)

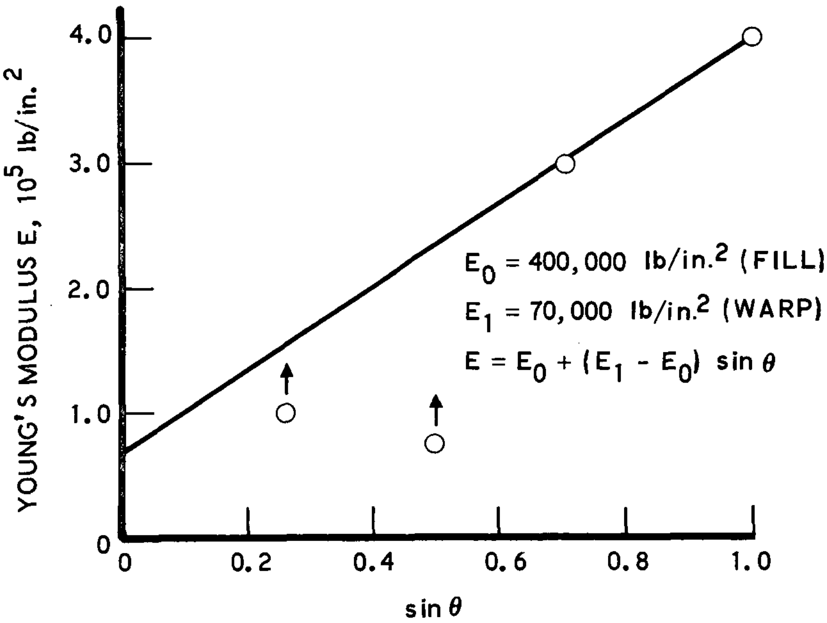


Fig. 5. Young's Modulus vs sin θ for θ = 0-, 15-, 30-, 45-, and 90-deg Off Fill

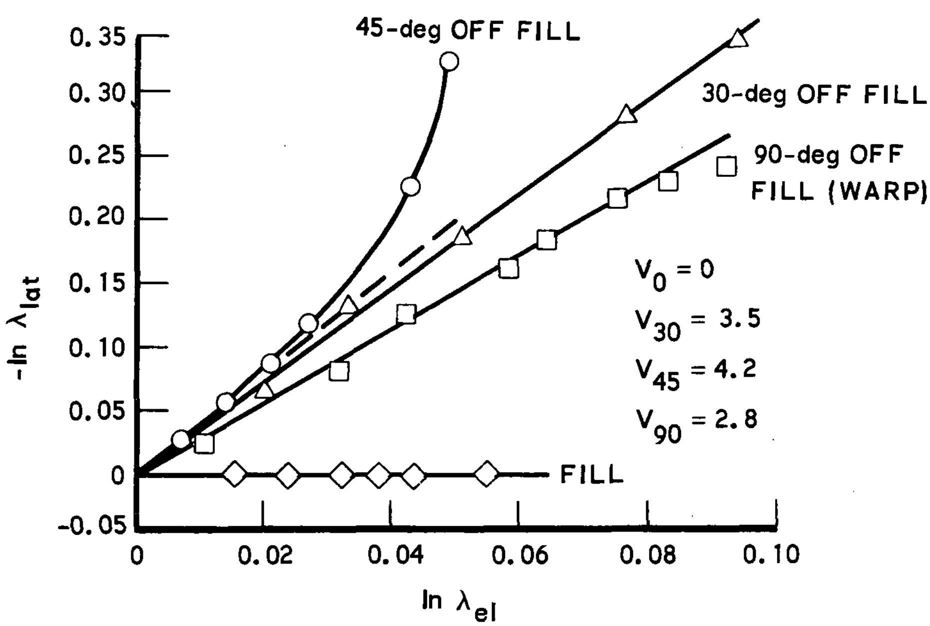


Fig. 6. Lateral Contractions vs Longitudinal Elongation for θ = 0-, 30-, 45-, and 90-deg Off Fill

would have to be included in the strain energy function to characterize the Kevlar 29. In Fig. 6, the lateral contraction in the fill case is essentially zero.

Thus, the properties of Kevlar 29 single-ply fabric can be summarized by stating that the material behaves linearly in the fill direction, with zero Poisson's ratio, whereas it is highly nonlinear in the warp direction, with an abnormally high value of Poisson's ratio. From this, it would be expected that the primary resistance to bullet penetration is provided by the fill fibers, because of their stiffness (high modulus) as well as the low Poisson's ratio, which indicates very little interaction with warp fibers.

B. Biaxial Loading

1. Bulge tests. It was noted in the preceding discussion that lateral strains were produced by stress applied in the longitudinal direction. Material response becomes complex under realistic loading conditions, where stresses are applied simultaneously in more than one direction. A very important subclass of the three-dimensional state of stress are membranes, where the stresses in one direction can be ignored compared to the stresses in the other two directions. The loading produced by a bullet impacting soft armor is one such case. Here, for regions not in contact with the bullet, the in-plane stresses are so much larger than the stresses occurring across the thickness of the fabric that the latter can be ignored and the loading condition treated as a biaxial state of stress.

A well-know technique for developing a biaxial state of stress in a membrane is the bulge test. The sample is clamped by a circular ring and the unsupported area subjected to uniform pressure loading, which is generally produced by hydrostatic pressure in a pressure vessel with the test material closing off one end. If the test sample is sufficiently thin, bending stresses can be ignored, in comparison to the in-plane or membrane stresses produced by the loading. Combined with the symmetrical geometry used, i.e., polar symmetry, a relatively simple stress field is developed in the radial and circumferential directions. In the case where the material is elastic, isotropic, and homogeneous, an approximate solution for the large deflection case has been found.[2] The central deflection is given by

$$d_0 = 0.662\, a \sqrt[3]{\frac{Pa}{Eh}} \qquad (9)$$

where

a is the radius of the loaded portion of the test sample

h is the test sample thickness

P is the applied (hydrostatic) pressure

The tensile stresses at the center and at the clamped boundary are, respectively,

$$(\sigma_r)_{r=0} = 0.423 \sqrt[3]{\frac{EP^2a^2}{h^2}} \qquad (10)$$

[2] S. Timoshenko, "Theory of Plates and Shells," New York, McGraw-Hill Book Co., Inc., 1940, p. 337.

and

$$\sigma_{r_{r=a}} = 0.328 \sqrt[3]{\frac{Ep^2 a^2}{b^2}} \tag{11}$$

Thus, the radial stresses are expected to vary only slightly over the membrane, with a slightly higher value occurring at the center as compared to the edge. The central deflection is expected to vary as the cube root of the applied pressure.

Because of the anisotropic character of the woven cloth configuration, the above relations do not strictly apply, but do give some guidance to probable behavior. Tests were performed with a single ply of 400/2 (36 × 36) Kevlar 29 fabric using an available, 6.31-in.-diameter pressure vessel. Because of the porous nature of the fabric, a very thin rubber sheet (dental dam material) was used under the single ply of material to provide a seal. The fluid used to develop the hydrostatic pressure was an oil-water mixture. A grid system of radial and circumferential lines, laid out on the fabric with the fill direction of the cloth along the 0- to 180-deg diameter and warp along the 90- to 270-deg diameter was used, together with a dial gauge, to obtain deflection data at selected pressures. Photographs were taken, looking straight down on the sample, to assist in the analysis. The deflection data are summarized in Table I. The data in Fig. 7 indicate that the central deflection does vary approximately as the one-third power of the pressure in spite of the anisotropic character of the fabric. The effects of anisotropy on the deformation of the cloth are also clearly evident, as can

Table I. Vertical Deflection of Membrane Under Hydrostatic Pressure at Various Radii

Off Fill, deg	Radius, in. 0	0.50	1.00	1.50	2.00	2.50	3.00	Ring
Pressure = 20 lb/in.^{2} (P = 15 lb/in.^{2} at end of measurement)								
0	0.471	0.462	0.429	0.375	0.295	0.196	0.081	0.744
30	0.476	0.467	0.438	0.389	0.319	0.220	0.086	0.751
45	0.478	0.470	0.443	0.394	0.320	0.225	0.094	0.751
60	0.484	0.478	0.454	0.409	0.343	0.241	0.105	0.759
90	0.487	0.482	0.459	0.412	0.344	0.248	0.104	0.762
120	0.463	0.457	0.432	0.387	0.310	0.216	0.081	0.743
135	0.465	0.457	0.429	0.384	0.310	0.210	0.086	0.747
150	0.468	0.460	0.429	0.378	0.304	0.203	0.086	0.747
180	0.471	0.462	0.426	0.372	0.293	0.199	0.077	0.753
210	0.476	0.466	0.434	0.385	0.317	0.210	0.084	0.754
225	0.478	0.469	0.439	0.395	0.322	0.224	0.100	0.761
240	0.484	0.475	0.450	0.402	0.332	0.239	0.108	0.761
270	0.488	0.482	0.458	0.413	0.345	0.251	0.110	0.763
300	0.463	0.458	0.430	0.384	0.312	0.222	0.085	0.741
315	0.465	0.458	0.428	0.382	0.308	0.215	0.033	0.740
330	0.468	0.460	0.429	0.384	0.306	0.205	0.087	0.744
Pressure = 50 lb/in.^{2} (P = 45 lb/in.^{2} at end of measurement)								
0	0.613	0.610	0.565	0.496	0.396	0.266	0.120	0.739
30	0.613	0.602	0.567	0.507	0.419	0.280	0.112	0.731
45	0.612	0.604	0.573	0.518	0.422	0.287	0.105	0.731
60	0.613	0.607	0.579	0.517	0.428	0.301	0.129	0.732
90	0.613	0.608	0.580	0.517	0.435	0.307	0.119	0.733
120	0.614	0.605	0.580	0.525	0.422	0.295	0.135	0.737
135	0.613	0.603	0.570	0.510	0.416	0.278	0.103	0.737
150	0.613	0.605	0.568	0.504	0.408	0.270	0.108	0.741
180	0.613	0.607	0.560	0.489	0.385	0.256	0.087	0.741
210	0.613	0.600	0.562	0.502	0.412	0.276	0.091	0.737
225	0.613	0.602	0.573	0.518	0.417	0.281	0.123	0.737
240	0.612	0.604	0.574	0.516	0.426	0.305	0.128	0.735
270	0.613	0.608	0.584	0.526	0.441	0.322	0.140	0.734
300	0.613	0.606	0.577	0.521	0.428	0.303	0.125	0.732
315	0.614	0.605	0.572	0.514	0.419	0.293	0.130	0.731
330	0.613	0.605	0.568	0.507	0.413	0.275	0.109	0.731
Pressure = 100 lb/in.^{2} (P = 90 lb/in.^{2} at end of measurement)								
0	0.874	0.857	0.800	0.710	0.588	0.403	0.188	0.735
30	0.871	0.859	0.817	0.735	0.613	0.428	0.175	0.735
45	0.872	0.862	0.820	0.738	0.587	0.392	0.177	0.735
60	0.874	0.864	0.821	0.724	0.578	0.395	0.178	0.738
90	0.874	0.861	0.807	0.710	0.574	0.403	0.175	0.740
180	0.874	0.850	0.785	0.692	0.557	0.384	0.175	0.740
210	0.871	0.857	0.812	0.747	0.633	0.459	0.197	0.740
225	0.872	0.861	0.828	0.758	0.629	0.452	0.202	0.740
240	0.874	0.866	0.835	0.760	0.632	0.456	0.200	0.739
270	0.874	0.868	0.837	0.761	0.638	0.457	0.189	0.737

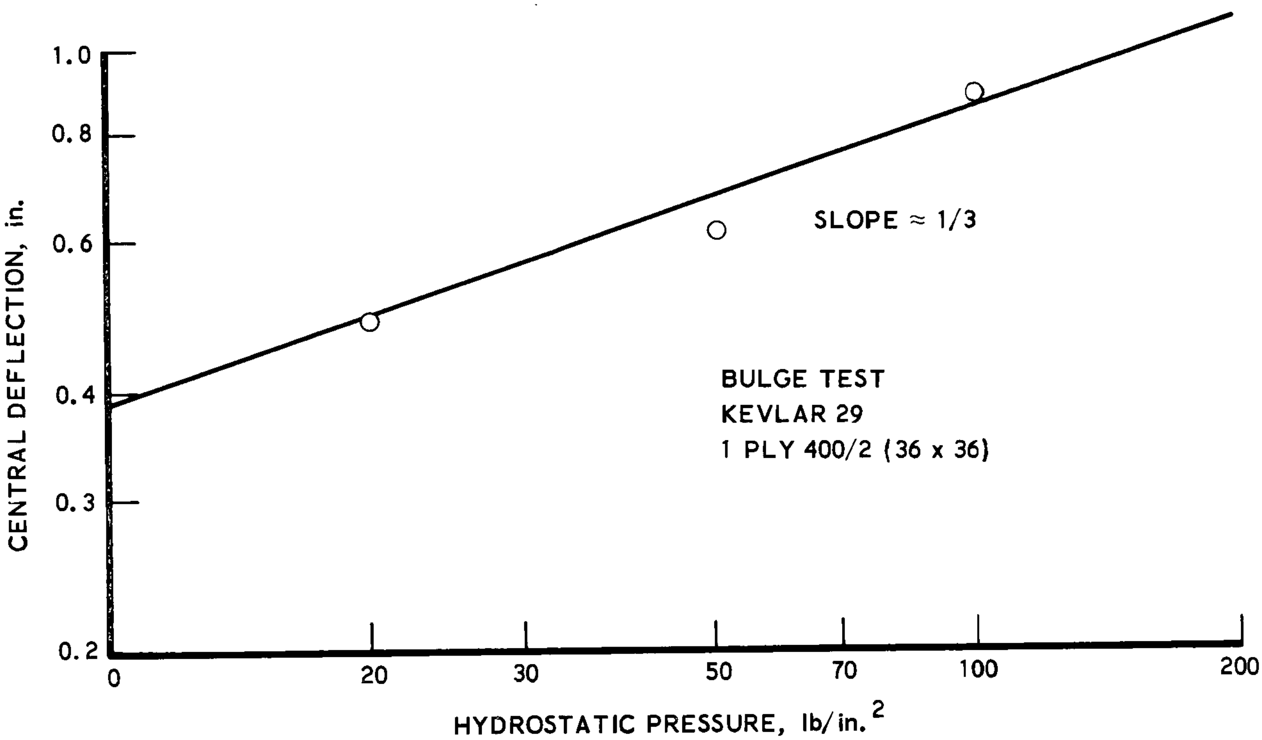


Fig. 7. Deflection vs Hydrostatic Pressure From Bulge Test

be seen in Figs. 8 through 10. The tests were not taken to failure because of a deficiency in the clamping technique, which permitted slippage of the fabric under the clamp at pressures of around 100 psi and above. A major redesign of the clamping technique would be required to alleviate this problem but was not undertaken because of the limited time for the investigation.

An assessment of the bulge test data must await development of a large-deflection, anisotropic material solution of the membrane problem. A rough estimate of the effective modulus E_e of the fabric can be obtained with Eq. (9) and the data. With a central deflection of 0.61 in. for the 50-psi loading, Eq. (9) gives $E_e = 4.1 \times 10^5$ psi. From Fig. 4, the elastic secant modulus for the warp and fill directions are 22×10^6 and 3.2×10^5 psi, respectively. This result indicates that the off-fill properties dominate fabric response under biaxial loading.

2. <u>Indentor tests.</u> With the anisotropic behavior of the Kevlar 29 fabric characterized, the general engineering approach is to apply the principles of continuum mechanics to the particular loading geometry involved. Since no adequate mathematical models exist that describe the behavior of a flexible fabric under ballistic loading, it became necessary both to develop a model and to acquire the data necessary for testing the model. Such data allow further qualitative analysis of various parameters.

The indentor test allowed geometric simulation of the ballistic interaction. With the fabric clamped in a circular ring, a quasi-static load was applied through a bullet-shaped indentor mounted on the cross head of the Instron testing machine (Fig. 11). Initially, a .38-caliber bullet was

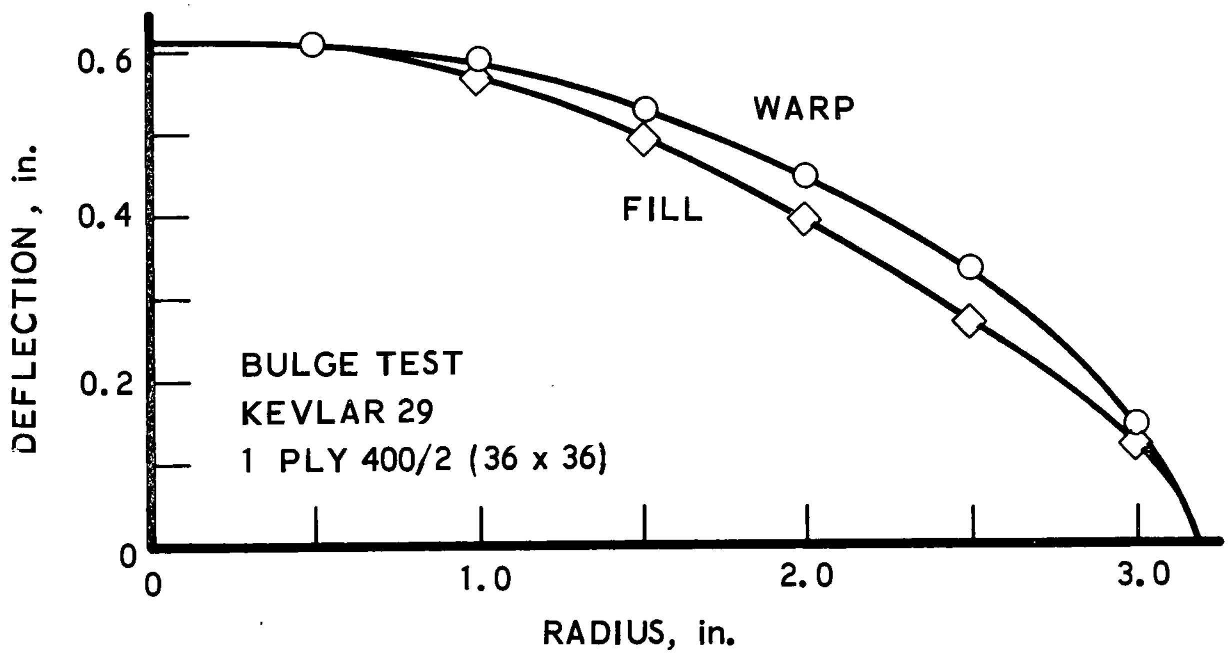


Fig. 8. Membrane Deflection vs Radius for Warp and Fill at P = 20 lb/in.^{2}

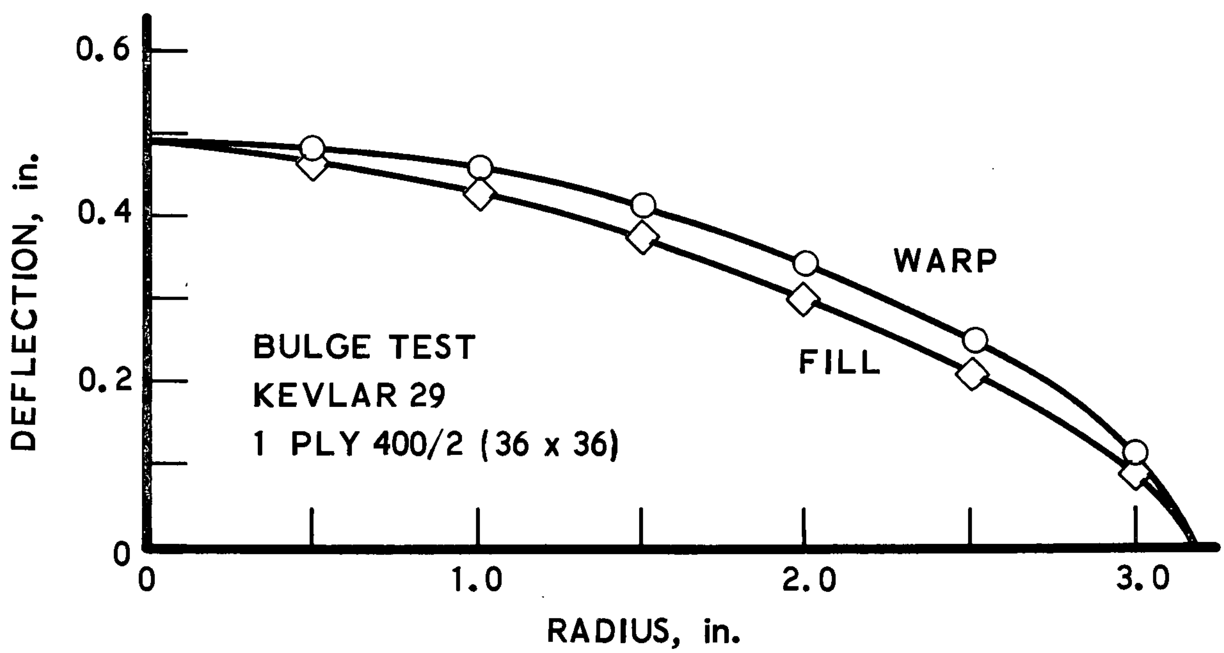


Fig. 9. Membrane Deflection vs Radius for Warp and Fill at P = 50 lb/in.^{2}

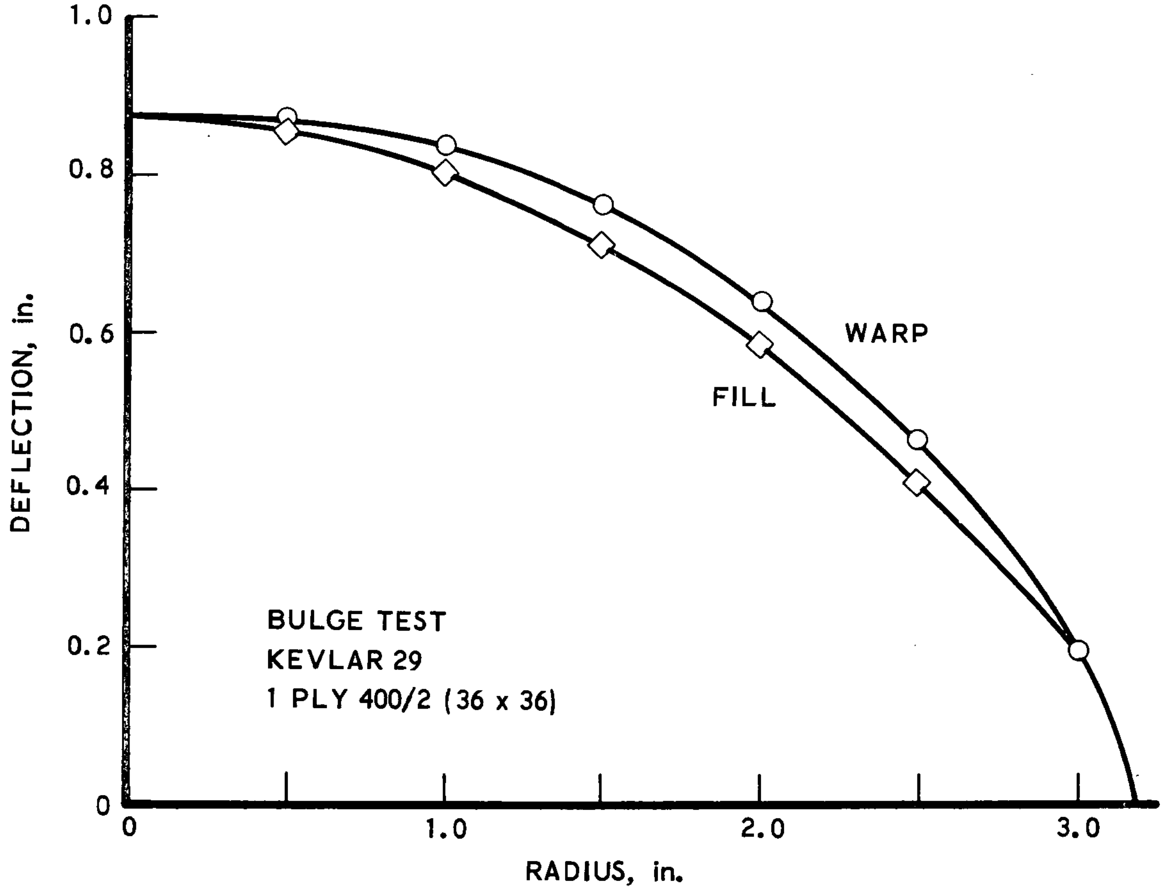


Fig. 10. Membrane Deflection vs Radius for Warp and Fill at P = 100 lb/in.^{2}

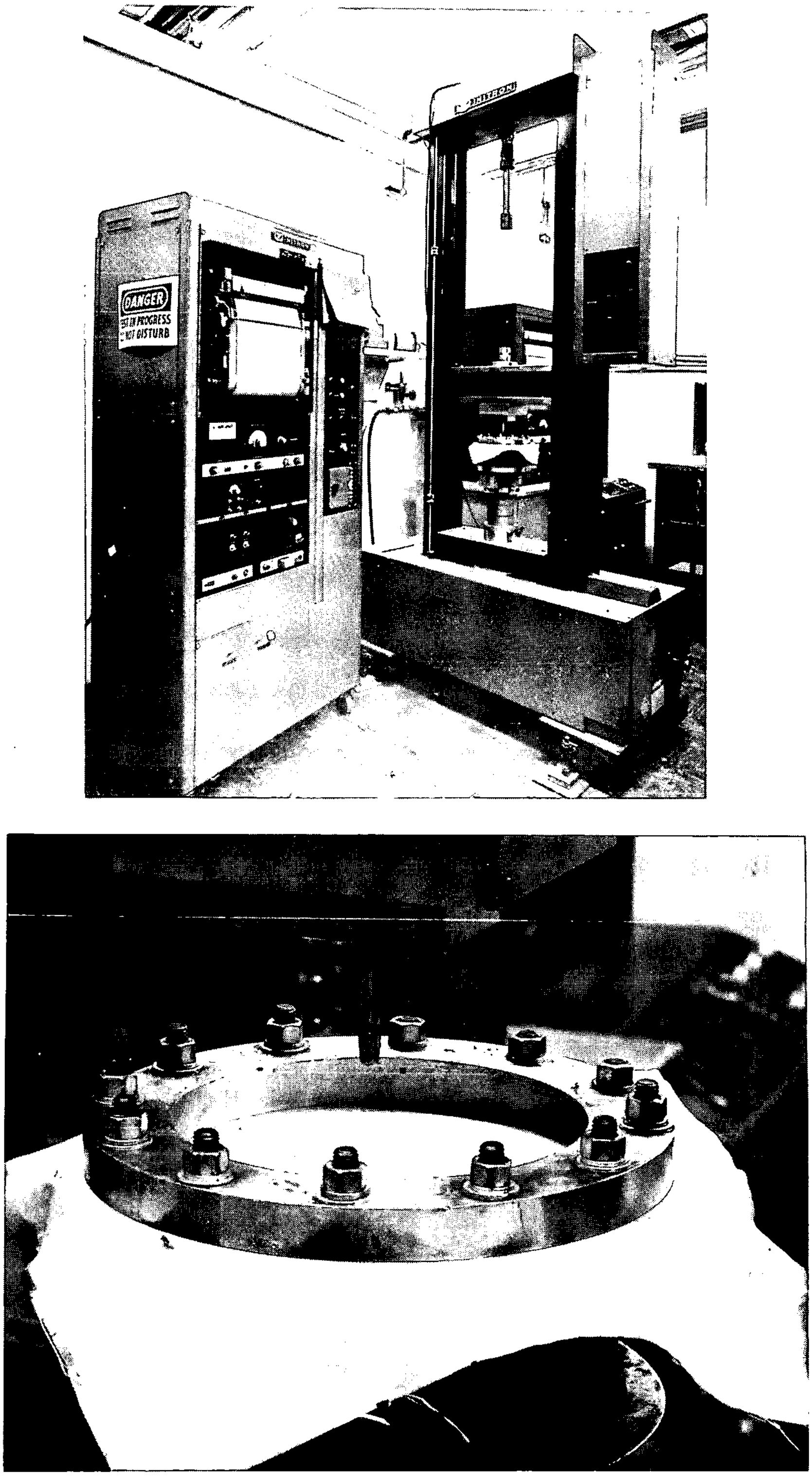


Fig. 11. Indentor Fixture Mounted in Instron Testing Machine

mounted on the end of a steel rod to provide a realistic geometry. In spite of the care taken to align the indentor with the center of the 10-in.-diameter fixture (also used for the pendulum impact tests described later) onto which the plies were clamped, the soft-lead bullets invariably failed in shear because of unsymmetrical loading, which is believed to be strongly influenced by the anisotropic character of the fabric. An elliptical indentation was formed in the fabric under the indentor, because of this anisotropy. Finally, a steel indentor having a 0.5-in. diameter and shaped to match a ballistically deformed soft-lead .38-caliber bullet was made and used for these tests and for the pendulum impact tests (Fig. 12).

Some typical load-displacement curves for various numbers of plies, and air and clay backing are shown in Fig. 13. The effect of clay backing was found by carrying out tests with 500-lb load level and making epoxy castings of the deformed surface for the cases of air backing, unconfined clay backing (by use of 7-in.-square blocks inside the 10-in.-diameter test fixture), and completely confined clay backing; i.e., completely filling the interior of the 10-in.-diameter test fixture. The contours in the warp and fill directions obtained from the epoxy castings are shown in Fig. 14. For the same static load, with the deformed bullet-shaped steel indentor, the central deflection is less for the confined-clay backing case than for either the air or unconfined clay. The yarns in the warp direction that pass through the indentor region have been uplifted in the outer annular region because of the displacement of the confined clay by the corresponding yarns in the fill direction. This effect is not evident in the air-backed and

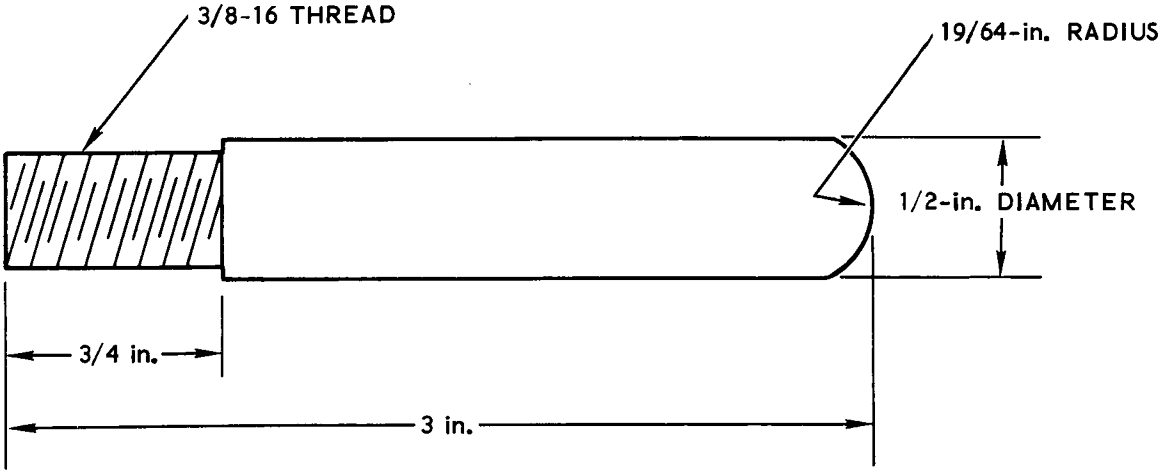


Fig. 12. Steel Indentor

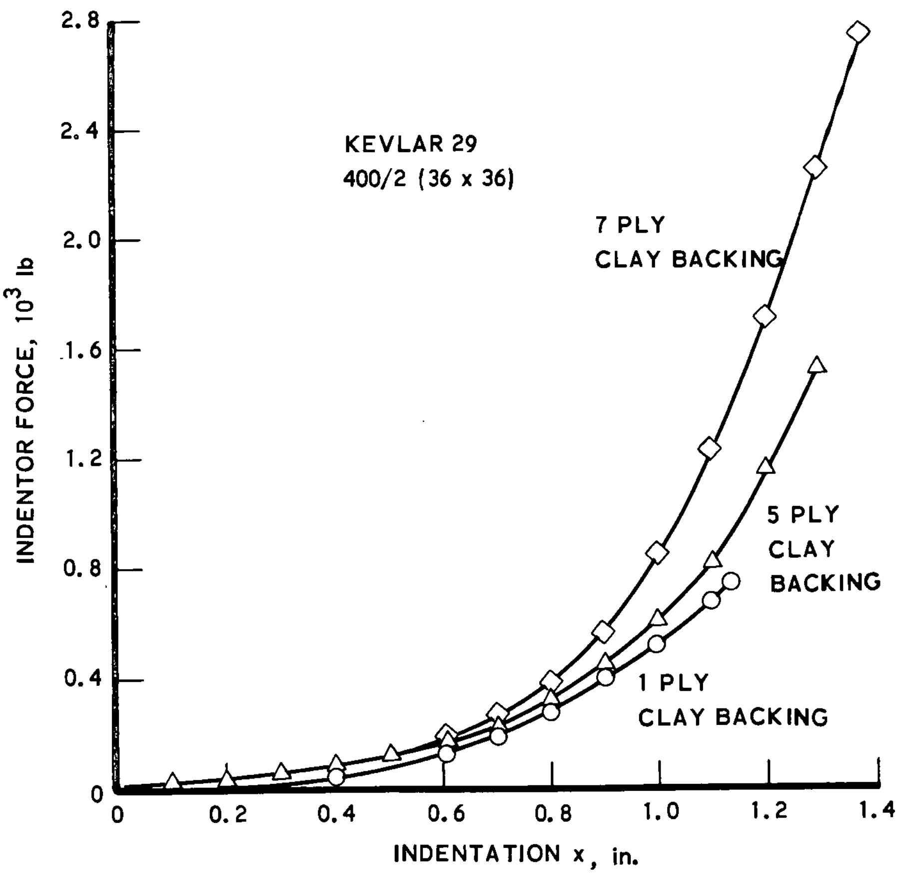


Fig. 13. Static Indentor

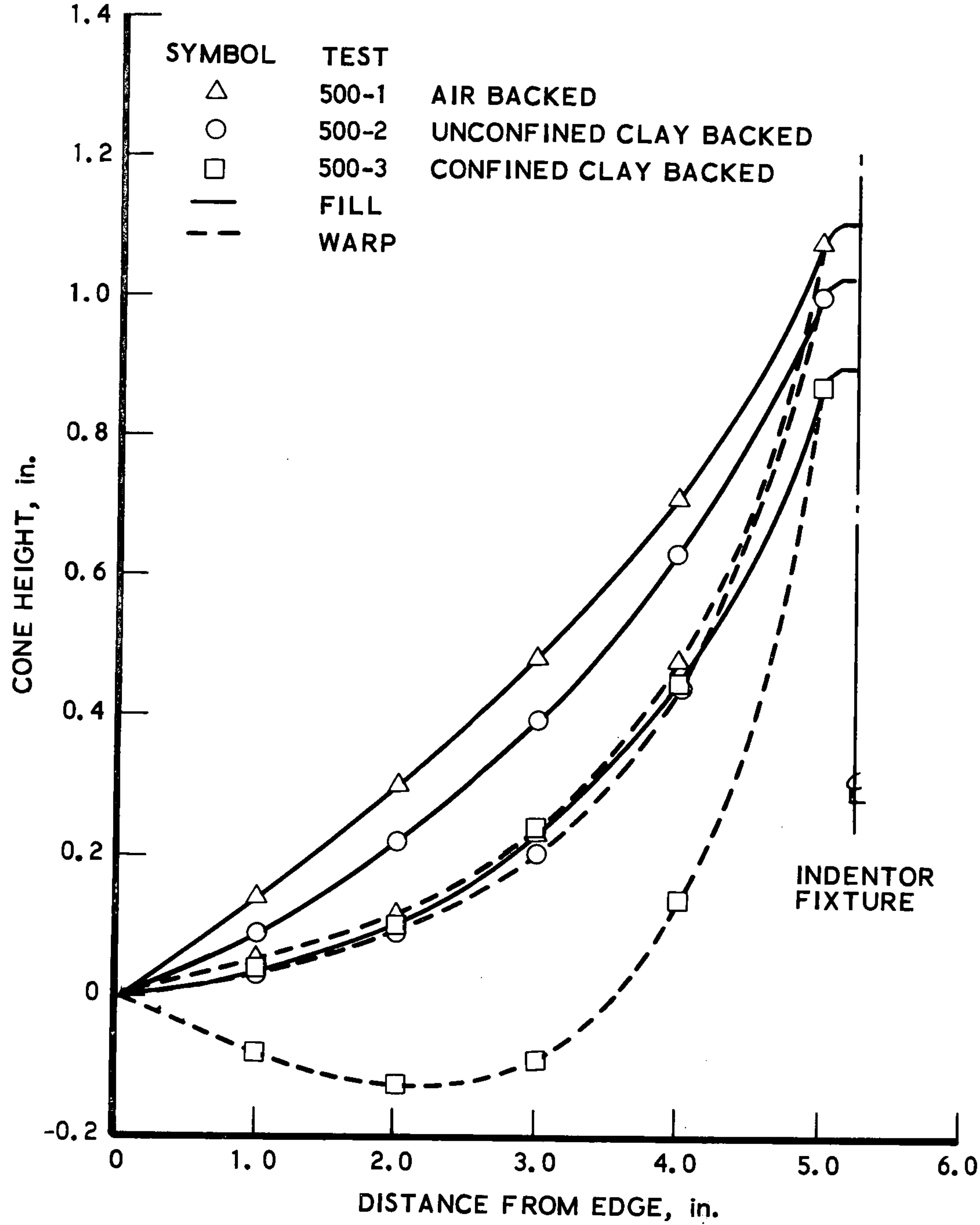


Fig. 14. Indentation Contour for Single-Ply 400/2 (36 × 36) Kevlar 29 Fabric

unconfined clay-backed cases (lateral expansion of the clay is essentially uninhibited in the latter case). The upward motion of the warp yarns plus the overall constraint produced by the clay reacting against the fabric accordingly result in a smaller central deflection for the confined clay-backed case. This is yet another aspect of the anisotropic character of the fabric.

The stress distribution in the fabric is far more complex for the localized loading than for the hydrostatic loading case. An analytical solution for these boundary conditions was initiated, but required numerical solution of three coupled, nonlinear, ordinary differential equations. Time did not permit solution and, consequently, verification of these equations. However, such an anlysis should allow prediction of the force-displacement (Fig. 13) behavior of the armor together with the distribution of stresses in the armor.

CHAPTER III. INTERMEDIATE LOADING RATE DYNAMIC TESTS

A. Description of Apparatus

An existing Charpy impact test machine was modified, as shown in Fig. 15, to provide an inexpensive tool for studying the dynamic response of the soft-fabric armor as a function of indentor energy, number of fabric plies, and backing material. The primary modification was the addition of a strain-gauged, steel indentor (Fig. 12), attached to the pendulum near the center of mass. This permits straight-forward recording of the indentor load-time history on an oscilloscope during the interaction with the target configuration. It was also necessary to add a bracket to the machine that could support the 10-in.-diameter sample test fixture (Fig. 15). (This sample test fixture was also used for static indentor tests on the Instron test machine and for a few shots at the ballistic range.) The height of drop of the pendulum was controlled by means of a heavy aluminum bar, notched and indexed at 1-in. intervals along its length. Because of physical constraints of the test apparatus, the minimum height of drop for the convenient use of this bar is 1.27 in., corresponding to a pendulum potential energy of 5.6 ft lb, which is well below the critical threshold for penetration of one ply of fabric. The largest pendulum potential energy used was 130 ft lb, which represents about half the full capacity of the apparatus.

The size (diameter) of the sample test fixture was selected to provide a reasonable compromise between the need for minimizing edge effects from the clamped boundary condition and the desire to minimize material costs.

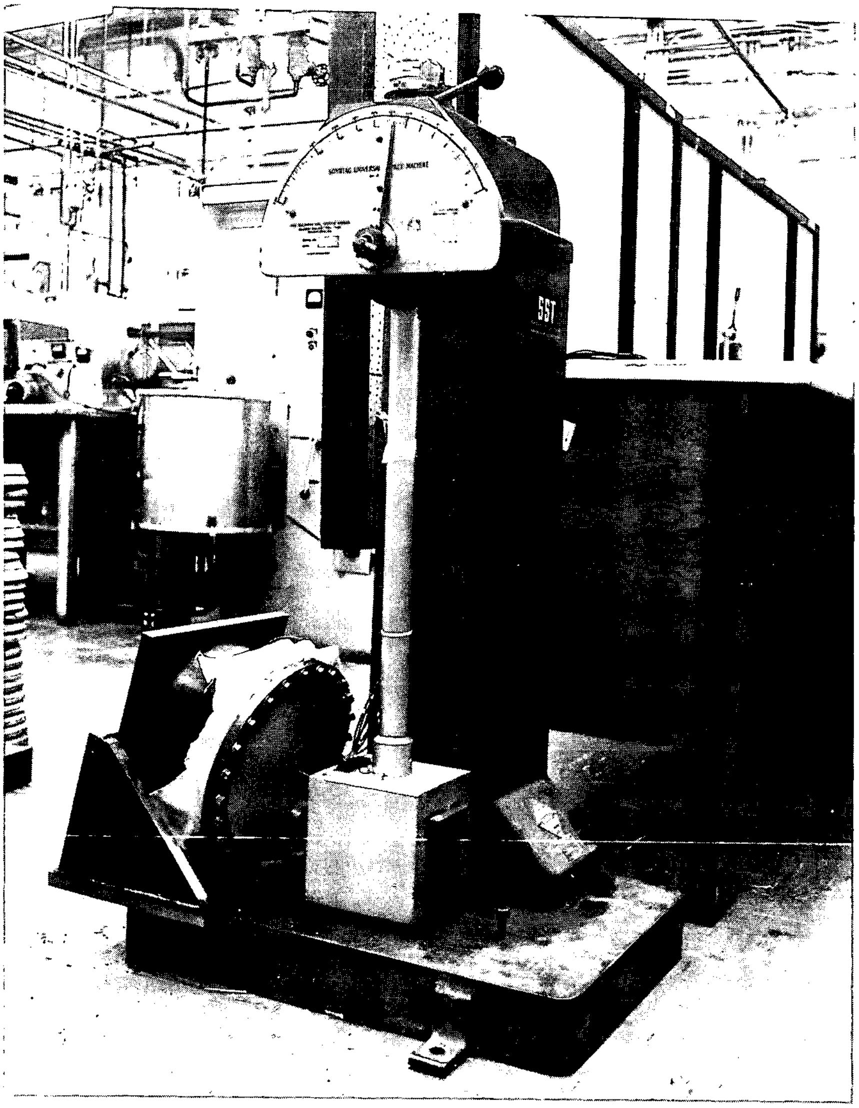


Fig. 15. Charpy Impact Test Machine and 10-in.-diameter Test Fixture

Preliminary experimentation with an existing, 6-in.-diameter test fixture suggested that effects from the clamped ring were significant with that size; hence, the larger (10-in.) diameter was chosen.

Load-time histories from the indentor were recorded on a Tektronic 535A oscilloscope by use of a Type 53/54K plug-in unit and a Polaroid camera attachment. Strain-gauge input to the oscilloscope was accomplished by means of a Model 870 Daytronic strain-gauge conditioner and amplifier with a Model 801 adaptor. The vertical (load) scale was adjustable to 250 lb/cm or 500 lb/cm with this equipment. Two Micromeasurements, Inc., strain gauges, ED-DY-125 CA-350, were used on the indentor. Triggering of the oscilloscope was set at a level of 100 lb, which was sufficient to prevent stray noise from starting the sweep prematurely. The sweep time was generally set at 5 msec/cm, except for impacts with gelatin backing, where it was necessary to use a 10-msec/cm timing.

B. Pendulum Potential Energy, Momentum, and Velocity

The maximum pendulum potential energy for each impact was determined from the vertical height above the rest position from which the center of mass of the pendulum was released. In practice, this was set by the position on the notched and indexed aluminum bar, used for holding the 53-lb pendulum until ready for the release. It is assumed that all of the pendulum potential energy is converted to kinetic energy when the pendulum reaches the bottom of the swing, at which point the indentor is in contact with the target material (Fig. 15) and pendulum. The pendulum energy at the point of impact is given by

$$E_P = mgh \tag{12}$$

where

h is the height to the center of mass

g is the gravitational constant

m is the pendulum mass

and the pendulum momentum by

$$M_P = m\sqrt{2gh} \tag{13}$$

If we denote the resisting force in the membrane (and backing material) as F(t), then

$$-F(t) = \frac{d}{dt}(mv) \tag{14}$$

where v is the velocity of the pendulum (we neglect the small loss in potential energy caused by the rise in the pendulum as it swings past center). Equation (14) can be integrated to yield

$$v(t) = \sqrt{2gh} - \frac{1}{m}\int_0^t F(t')\,dt' \tag{15}$$

where F(t) dt is simply the trace of the oscilloscope. Conservation of momentum and Eq. (13) imply that, for v(t) = 0,

$$m \sqrt{2gh} = \int_0^{t_1} F(t)\, dt \tag{16}$$

Thus, the time t_1, which corresponds to the instant of zero velocity and maximum deflection, can be evaluated by plotting the integral in Eq. (16) versus time and choosing t_1 such that Eq. (16) holds.

We can now integrate Eq. (15) again to obtain

$$x(t) = t \sqrt{2gh} - \frac{1}{m} \int_0^{t} dt' \int_0^{t'} F(t'')\, dt'' \tag{17}$$

or

$$x(t) = t \left[\sqrt{2gh} - \int_0^{t} \frac{F(t')}{m}\, dt' \right] + \int_0^{t} \frac{F(t')}{m}\, t'\, dt' \tag{18}$$

which, for $t = t_1$, becomes

$$d = \int_0^{t_1} \frac{F(t)}{m}\, t\, dt \tag{19}$$

where d is the maximum deflection of the membrane. In practice, d is obtained by plotting the integral, Eq. (18), and graphically integrating over the interval $0 < t < t_1$. Equation (18) yields the travel x(t) of the indentor as a function of time. Since time dependence of the force is measured directly, we further know the force as a function of position. This information will allow verification of analytical or numerical models as they are developed. Typical response of displacement versus time and velocity versus time are plotted in Figs. 16 and 17.

The maximum deflection d calculated from Eq. (19) agrees fairly well with that recorded by the pointer on the pendulum impact tester. However, the values of deflection measured from the epoxy castings of the cavity are considerably smaller (Table II). This discrepancy implies that considerable elastic spring back is occurring in the clay.

Table II. Depth of Clay Cavity

No. of Plies	Backing Material	Peak Load, lb	Maximum Indentation		
			Calculated Depth d, in.	Measured Depth of Cavity d_c, in.	Calculated Elastic Recovery d_e, in.
3	Air	790	0.74		
3	Air	775	1.13		
3	Clay	1050	1.47	0.73	0.49
3	Clay	1225	1.55	0.54	0.74
5	Clay	2350	1.64	0.95	0.79
5	Clay	2425	1.86	0.96	0.82

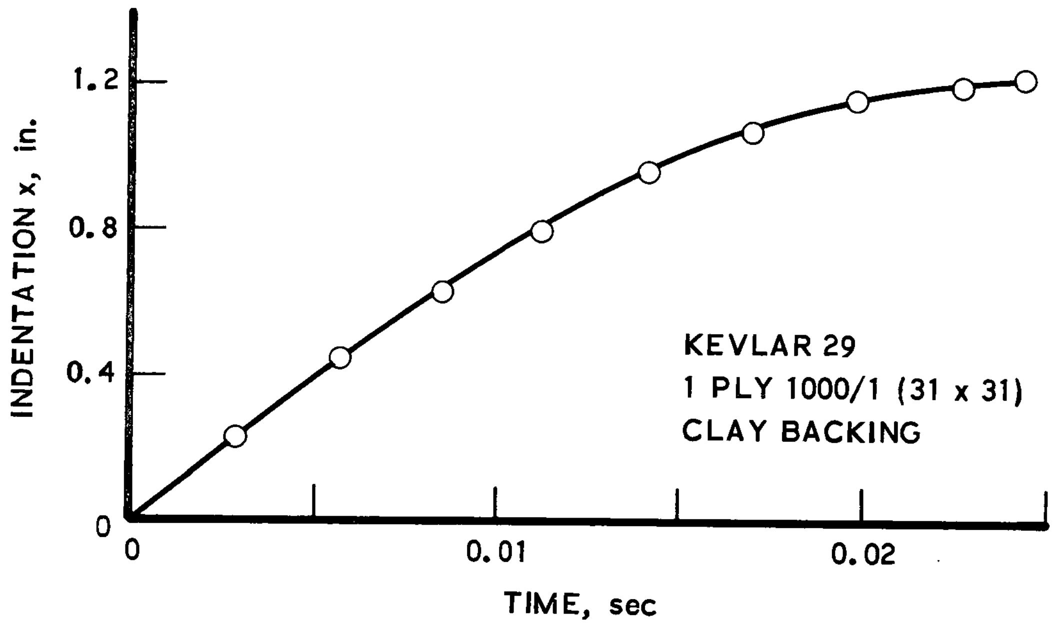


Fig. 16. Indentation vs Time for Pendulum Impact

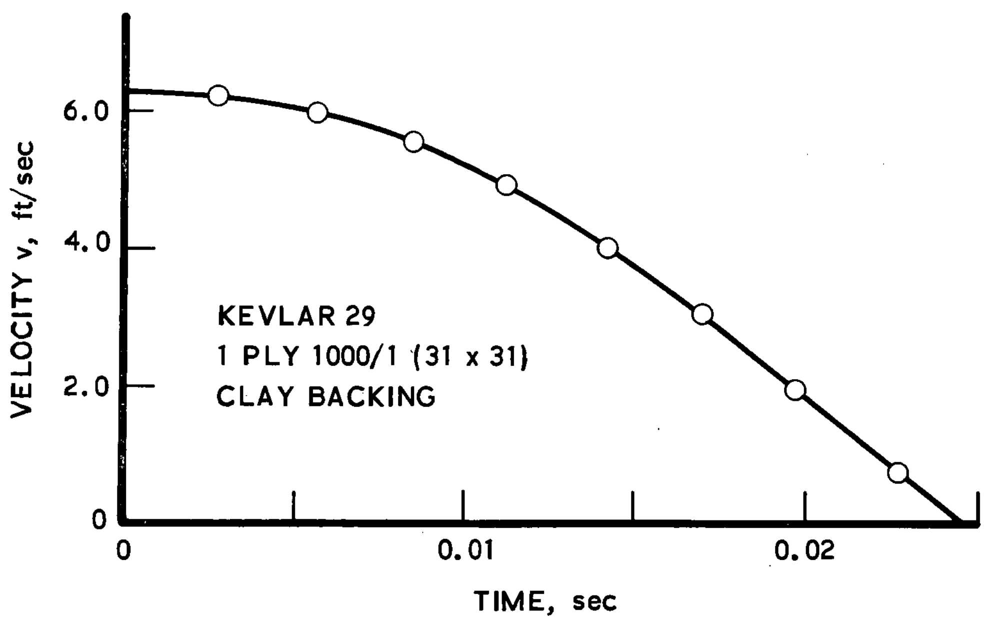


Fig. 17. Velocity vs Time for Pendulum Impact

As a first-order approximation, we consider the elastic recovery of a material subjected to a concentrated load, which is given by the punch formula

$$d_e = \frac{(1 - \upsilon)P_I a}{G} \tag{20}$$

where

d_e is the elastic recovery of indentation

P is the pressure of indentor

a is the radius of indentor

G is the shear modulus of medium (clay)

Under the assumption that $\upsilon = 1/3$ for clay, Eq. (20) can be written as

$$d_e = \frac{8F}{3\pi aM} \tag{21}$$

where

F is the force of indentor

a is the radius of indentor

M is the confined bulk modulus

The confined bulk modulus of the clay was measured on the Instron tester by placing the clay in a piston-cylinder device, compressing the clay, and measuring load versus displacement. This procedure yielded M = 2500 lb/in^2. Since the radius of the back face of the armor is poorly defined, a cone angle of 90 deg was assumed, and a was taken to be equal to d_c, where d_c is the measured depth of the clay cavity. Values of d_e calculated in this manner are reported in Table II.

In Table II, we present the total indentation calculated from Eq. (19) and confirmed by pointer measurements; we also present the measured indentation to the base of the clay cavity. The difference between these two depths should equal the elastic spring back of the clay. This spring back was calculated in Eq. (21) and presented in Table II. The agreement is quite good.

Having analyzed the dynamics of the indentation of a membrane by a pendulum by means of the pendulum impact test, we obtain the information shown in Fig. 18, i.e., the indentation (displacement) of the membrane as a function of applied force. If the pendulum impact test were carried out statically by holding the pendulum at a given indentation, the force registered by the sensor would be the same as that measured in the dynamic test. The validity of this assumption is based on the range of loading rates involved in the pendulum impact test; the inertia of the membrane is negligible with respect to the strain energy in the membrane. This is not true for the case of bullet impact; this analysis will require a more elaborate mathematical model.

Assuming quasi-static loading for the pendulum impact test, nonlinear membrane theory can be used to analyze indentation of a membrane by a concentrated load, and, consequently, impact of soft armor by a bullet, with the proper addition of the dynamic terms. The theory assumes that the fibers possess only elastic tensile stiffness, i.e., they have no bending stiffness. The results of such an analysis can be incorporated into routine, inexpensive computer codes. The results of such a computation can then be compared with pendulum and indentor data. Such a computation will predict the force-displacement curve shown in Fig. 18. Once the analysis is verified, the necessary additions can be incorporated for predicting ballistic response.

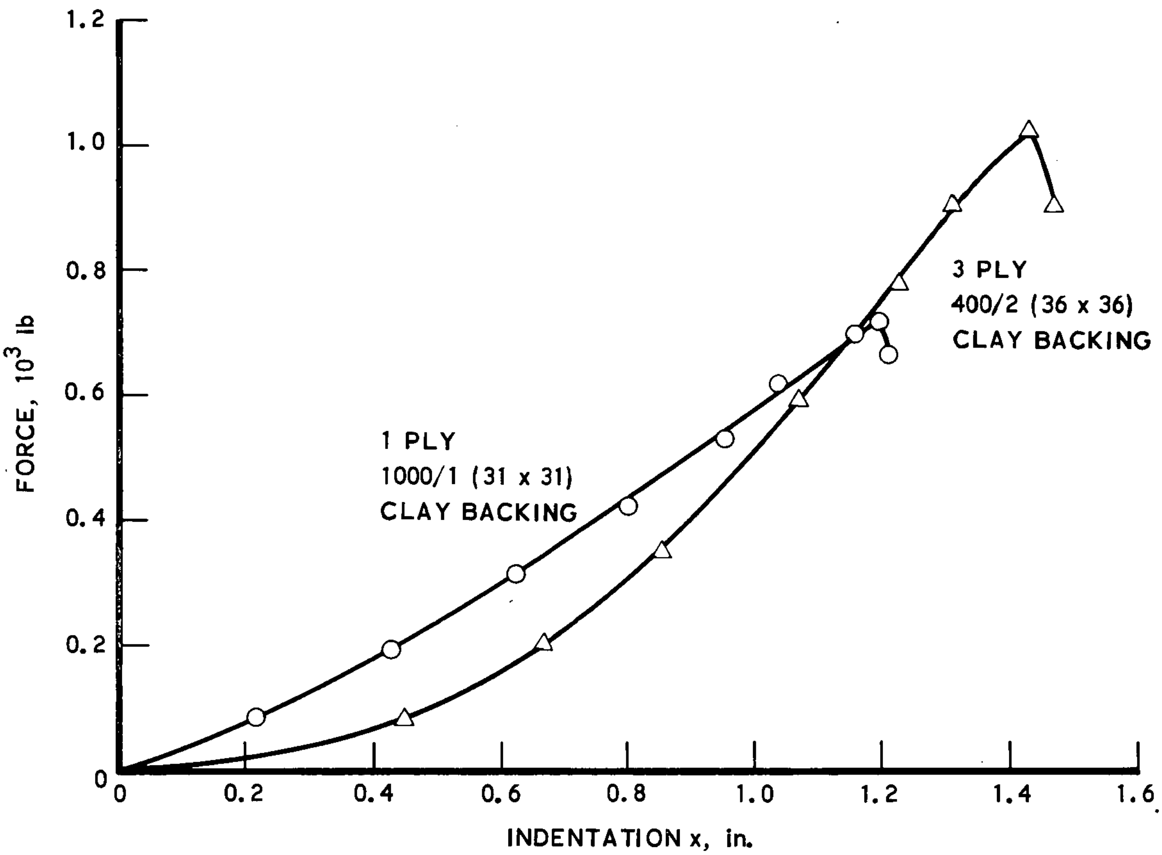


Fig. 18. Pendulum Impact

C. Test Results

The test data for the standard 400/2 (36 × 36) Kevlar 29 fabric are summarized in Table III. Impact conditions, i.e., height of pendulum drop, potential energy, momentum, and velocity, are recorded according to air, clay, or gelatin backing material and number of plies of fabric. The peak load, time to peak load, total time for the interaction, and measured total impulse (area under the load-time curve) for each impact from the oscilloscope are also recorded in Table III. The occurrence of penetration or nonpenetration of the fabric is likewise recorded.

The data are for virgin fabric only, i.e., for material that has not been previously impacted. When more than one ply was used in a test, the plies were oriented with the fill yarns in a parallel orientation, running in the same direction for each ply. A few special tests with the 1000/1 (31 × 31) Kevlar 29 fabric are reported in Table IV.

After each impact using clay backing material, a postimpact epoxy casting was taken of the cavity in the clay. From the casting, it is possible to estimate cavity volume and the general shape of the deformed surface of the fabric while under load. Because of the elastic spring back of the clay backing material, correction factors would have to be applied to measurements made from the cavities. The rather time-consuming graphical integration required to calculate maximum deflection was not accomplished for most of the data.

Typical oscilloscope traces are given in Fig. 19 for one ply of fabric and each of the backing materials. The pendulum energies are not the same

Table III. Summary of Pendulum Impact Test Data for 400/2 (36 × 36) Kevlar 29 Fabric at Pendulum Weight = 53 lb

No. of Plies	Vertical Height of Drop h, in.		Pendulum Potential Energy, ft lb	Pendulum Velocity v, ft/sec	Pendulum Momentum mv, lb sec	Measured Peak Load, lb	Time to Peak Load, msec	Total Loading Time, msec	Measured Impulse, lb sec	Results[a]
	Measured	c.g.								
Air-Backed Configuration										
1	2.25	1.21	5.62	2.61	4.31	180	22.0	45.0	3.5	NP
↓	4.25	2.74	12.1	3.83	6.32	350	17.5	42.0	5.25	NP
	5.25	3.46	15.3	4.30	7.10	425	17.5	39.0	6.62	NP
	5.75	3.88	17.1	4.55	7.50	430	17.5	17.5	2.25	CP
	6.25	4.27	18.8	4.78	7.88	475	14.0	14.0	3.32	CP
2	5.25	3.46	15.3	4.3	7.1	525	18.0	38.0	7.05	NP
↓	5.25	3.46	15.3	4.3	7.10	600	19.5	39.5	8.38	NP
	7.25	5.02	22.2	5.2	8.6	830	19.0	36.0	10.55	NP
	8.25	5.88	25.9	5.6	9.25	825	19.0	35.0	9.86	NP
	9.25	6.63	29.2	6.0	9.81	775	14.0	14.0	3.0	CP
	11.25	8.25	36.5	6.6	10.9	910	14.0	14.0	3.38	CP
3	4.25	2.74	12.1	3.8	6.3	490	17.0	31.5	6.50	NP
↓	4.25	2.74	12.1	3.8	6.3	550	19.5	36.5	---	NP
	5.25	3.46	15.3	4.3	7.1	790	19.5	33.5	---	NP
	6.25	4.27	18.8	4.8	7.9	775	19.5	36.5	8.3	NP
	11.25	8.25	36.5	6.6	10.9	1200	16.5	29.5	14.0	NP
	14.25	10.69	47.2	7.6	12.4	1175	11.5	11.5	3.8	CP
	18.25	14.0	61.9	8.7	14.3	1300	12.5	12.5	---	CP
4	14.25	10.69	47.2	7.6	12.4	1250	17.0	30.0	12.8	NP
↓	14.25	10.69	47.2	7.6	12.4	1675	17.0	30.5	16.9	NP
	14.75	11.06	48.8	7.7	12.7	1400	17.5	30.0	13.8	NP
	18.25	14.0	61.9	8.7	14.3	1000	13.0	13.0	5.3	CP
Gelatin-Backed Configuration (paper barrier + gelatin + clay)										
1	3.25	2.00	8.84	3.3	5.39	250	30.0	60.0	6.25	NP
↓	4.75	3.08	13.58	4.1	6.70	380	32.0	62.0	8.25	NP
	5.75	3.88	17.1	4.6	7.50	460	30.0	60.0	8.75	NP
	6.25	4.27	18.8	4.8	7.88	540	30.0	30.0	5.25	CP

[a]NP - No Penetration

CP - Complete Penetration

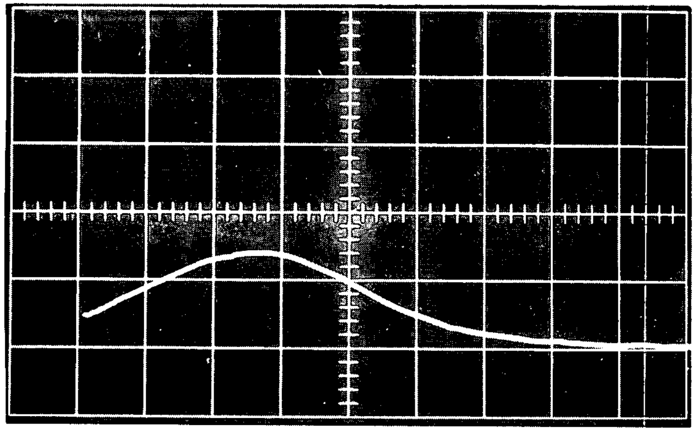
Table III. Summary of Pendulum Impact Test Data for 400/2 (36 × 36) Kevlar 29 Fabric at Pendulum Weight = 53 lb (Continued)

No. of Plies	Vertical Height of Drop h, in.		Pendulum Potential Energy, ft lb	Pendulum Velocity v, ft/sec	Pendulum Momentum mv, lb sec	Measured Peak Load, lb	Time to Peak Load, msec	Total Loading Time, msec	Central Deflection, in.	Measured Impulse, lb sec	Results[a]
	Measured	c.g.									
Clay-Backed Configuration											
1	5.75	3.88	17.1	4.6	7.50	325	19.0	42.0	0.70	6.5	NP
	8.25	5.88	25.9	5.6	9.25	525	22.5	41.0	0.88	9.0	NP
	9.25	6.63	29.2	6.0	9.81	575	20.0	39.0	0.76	9.4	NP
	9.75	7.00	30.9	6.1	10.1	600	21.6	21.6	2.07(0.80)	4.9	CP
2	8.25	5.88	25.9	5.6	9.25	590	22.0	39.0	0.66	9.0	NP
	11.25	8.25	36.5	6.6	10.9	880	22.0	37.0	0.79	12.0	NP
	13.25	9.94	43.9	7.3	12.0	990	21.5	37.0	0.83	13.4	NP
	14.25	10.69	47.2	7.6	12.4	1000	20.5	34.0	0.83	12.1	NP
	15.25	11.44	50.5	7.8	12.9	1050	17.5	17.5	1.16(0.71)	4.8	CP
3	7.25	5.02	22.2	5.2	8.6	575	23.0	395	0.58	9.1	NP
	13.25	9.94	43.9	7.3	12.0	1050	20.5	35.0	0.73	12.2	NP
	15.25	11.44	50.5	7.8	12.9	1225	19.5	33.0	0.54	13.3	NP
	17.25	13.13	58.0	8.4	13.8	1375	17.5	31.0	0.78	15.5	NP
	19.25	14.75	65.2	8.9	14.7	1400	16.0	30.5	0.78	16.0	NP
	21.25	16.88	72.7	9.4	15.5	1376	15.5	15.5	2.17(0.84)	5.9	CP
4	22.75	17.64	78.0	9.7	16.0	1750	17.0	29.5	0.86	17.4	NP
	23.25	18.13	80.1	9.9	16.3	1600	17.0	28.0	0.80	16.0	NP
	26.94	21.13	93.4	10.6	17.6	2000	16.5	16.5	1.45(0.99)	12.4	CP
5	31.25	24.82	109.7	11.5	19.0	2350	15.5	26.0	0.95	23.5	NP
	34.25	27.38	121.0	12.1	20.0	2425	15.5	26.0	0.96	23.0	NP
	35.75	28.75	127.1	12.4	20.5	2500	16.0	25.5	1.01	24.5	NP
	36.75	29.56	130.7	12.6	20.8	2150	14.5	14.5	2.17(0.98)	11.0	CP

[a]NP - No Penetration

CP - Complete Penetration

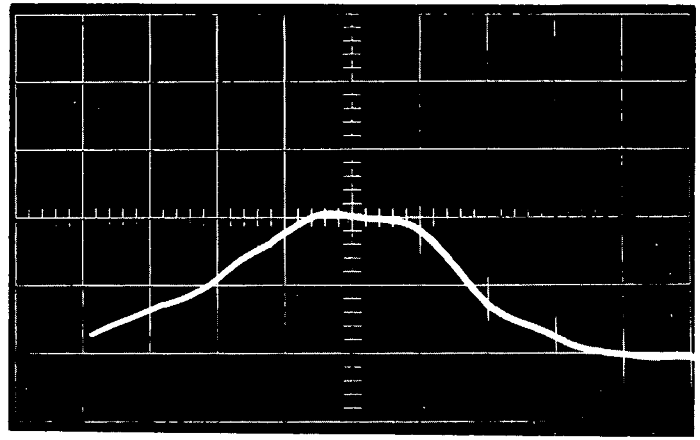
LOAD



TIME

AIR BACKING, E_p = 12 ft lb,
5 msec/cm, 250 lb/cm

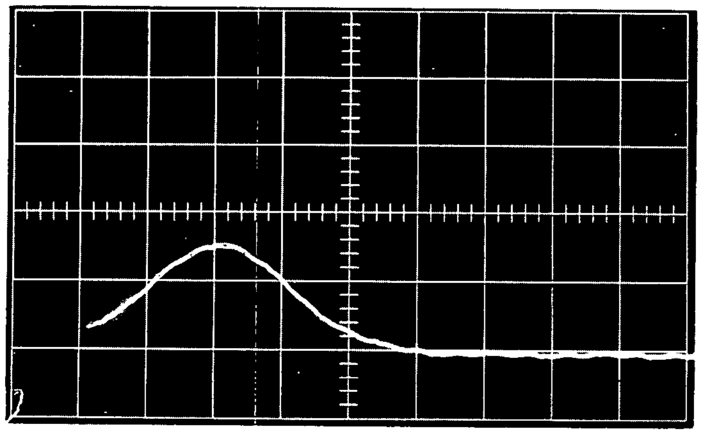
LOAD



TIME

CLAY BACKING, E_p = 26 ft lb,
5 msec/cm, 250 lb/cm

LOAD



TIME

GELATIN BACKING, E_p = 13.6 ft lb,
10 msec/cm, 250 lb/cm

Fig. 19. Typical Load-Time Histories for Single-Ply Configuration

Table IV. Summary of Pendulum Impact Test Data for 1000/1 (31 × 31) Kevlar 29 Fabric for Air-Backed Configuration

No. of Plies	Vertical Height of Drop h, in.		Pendulum Potential Energy, ft lb	Pendulum Velocity V, ft/sec	Pendulum Momentum mv, lb sec	Measured Peak Load, lb	Time to Peak Load, msec	Total Loading Time, msec	Measured Impulse, lb sec	Results[a]
	Measured	c.g.								
1	3.25	2.00	8.84	3.27	5.39	360	25	50	7.4	NP
	4.75	3.08	13.6	4.06	6.70	480	21	46.5	8.2	NP
	5.25	3.46	15.3	4.3	7.1	500	24	47	7.0	NP
	5.75	3.88	17.1	4.6	7.5	610	27	50	9.9	NP
	6.25	4.27	18.8	4.8	7.9	650	24	47	9.5	NP
	6.75	4.65	20.5	5.0	8.2	750	22	48	9.8	NP
↓	7.0	4.84	21.4	5.1	8.4	510	14.5	14.5	2.5	P

[a] NP - No Penetration

P - Penetration

in each case. The loading and unloading portions are generally symmetrical about the peak load, when no penetration occurs. Trace irregularities occur on penetration, in which case, the load drops to zero and oscillates around the zero position during the remainder of the oscilloscope sweep. Other irregularities might be due to slipping of the fabric under the clamping ring or to partial failure of the individual yarns under the indentor.

The data have been plotted in various ways to indicate trends. Figures 20 and 21 give peak load versus pendulum potential energy for air and clay backing materials, respectively. Penetration for the various ply configurations are indicated on the curves. The effect of varying the backing material with the single-ply configuration can be seen in Fig. 22. The variation of peak load with pendulum energy for a single ply of the 1000/1 (31 × 31) fabric is shown in Fig. 23.

Initial tests with gelatin used for the backing material resulted in extremely low penetration energies. The lowered failure resistance of the fabric was attributed to material degradation that resulted from the presence of water, which had condensated on the cold gelatin blocks. Subsequent uniaxial tensile tests on wet specimens showed no degradation of ultimate tensile strength when wet. It was concluded that the lowered penetration resistance of the wet fabric resulted from yarn lubrication by the water; the wet yarns were more easily pushed aside by the indentor, thus allowing penetration without physically breaking the yarns. This hypothesis was verified by inserting paper between the cold gelatin and Kevlar 29 fabric, which brought the penetration energies up to those measured with the air and clay backing.

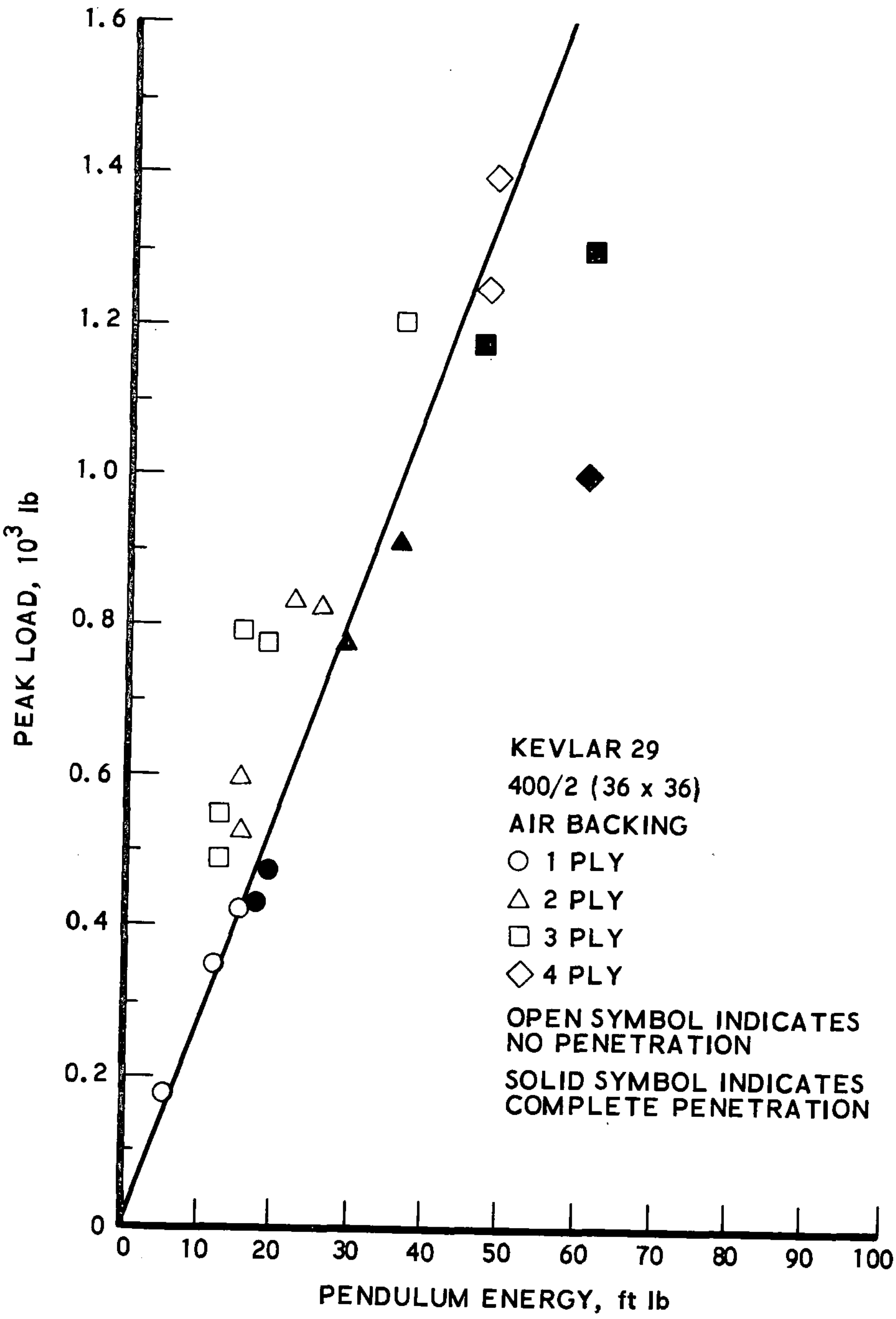


Fig. 20. Peak Impact Load vs Pendulum Energy for Pendulum Impact for Air-Backed Configuration

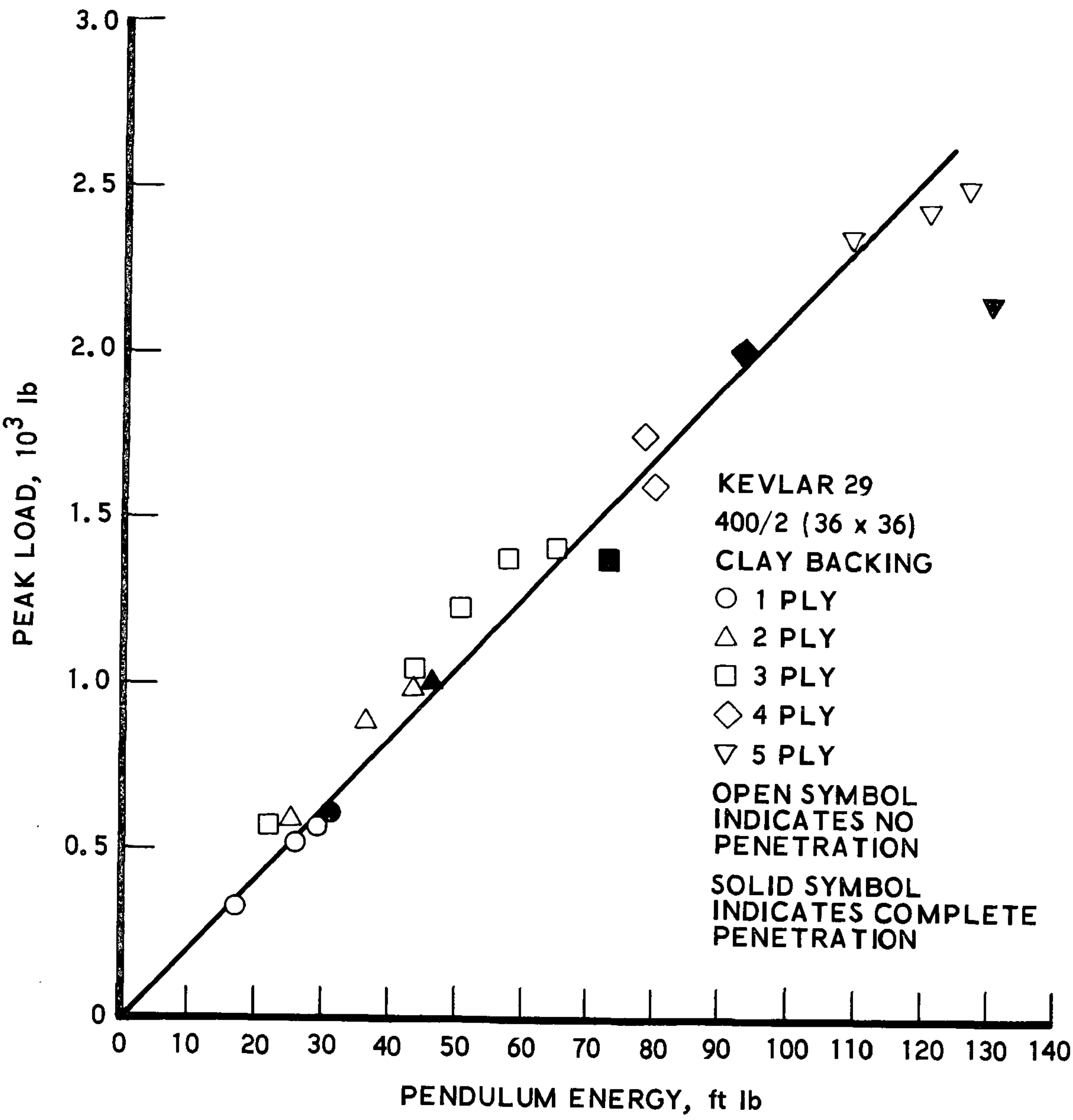


Fig. 21. Peak Load vs Pendulum Energy for Pendulum Impact for Clay-Backed Configuration

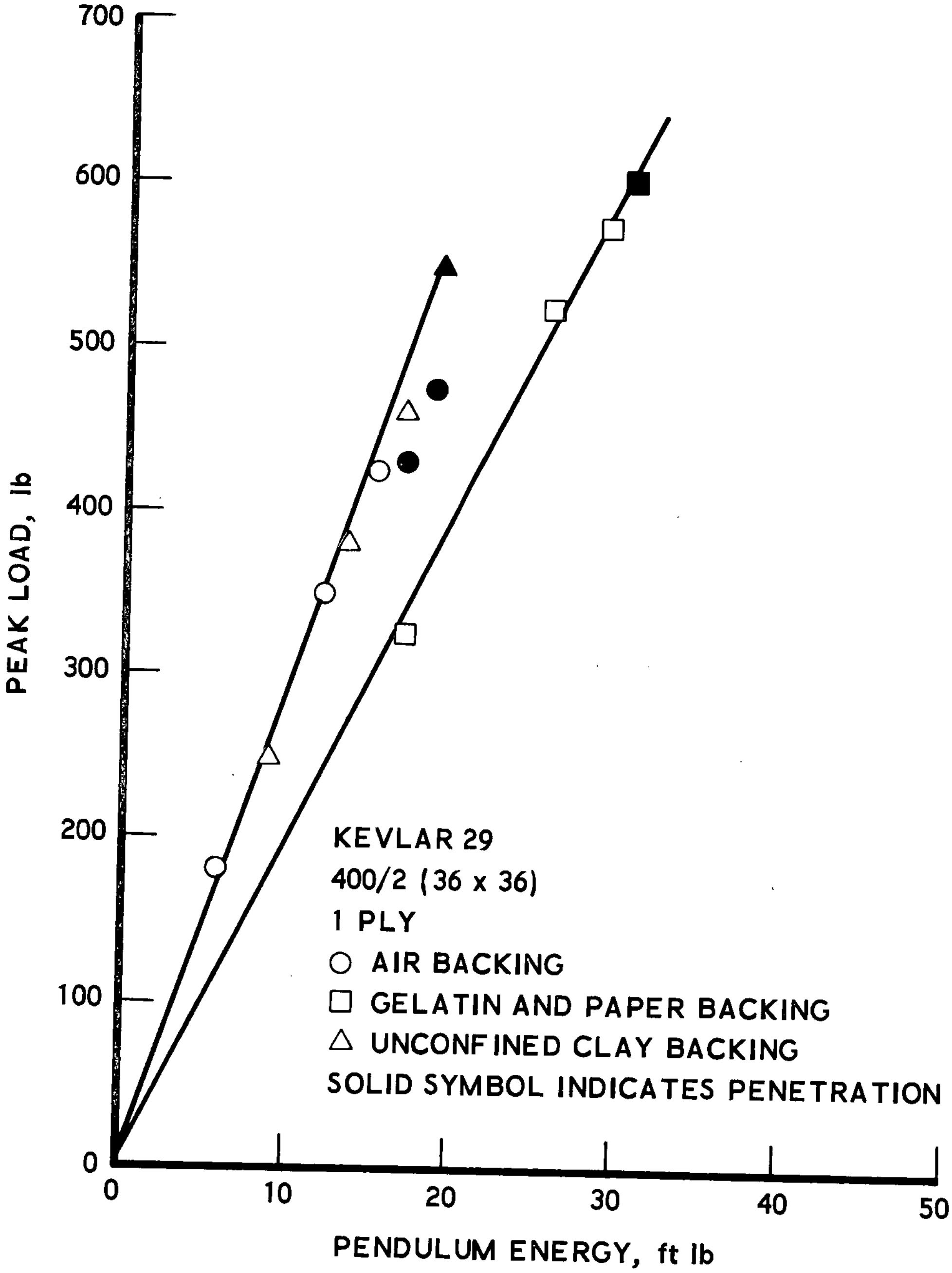


Fig. 22. Peak Impact Load vs Pendulum Energy for 400/2 (36 × 36) Kevlar 29 Fabric

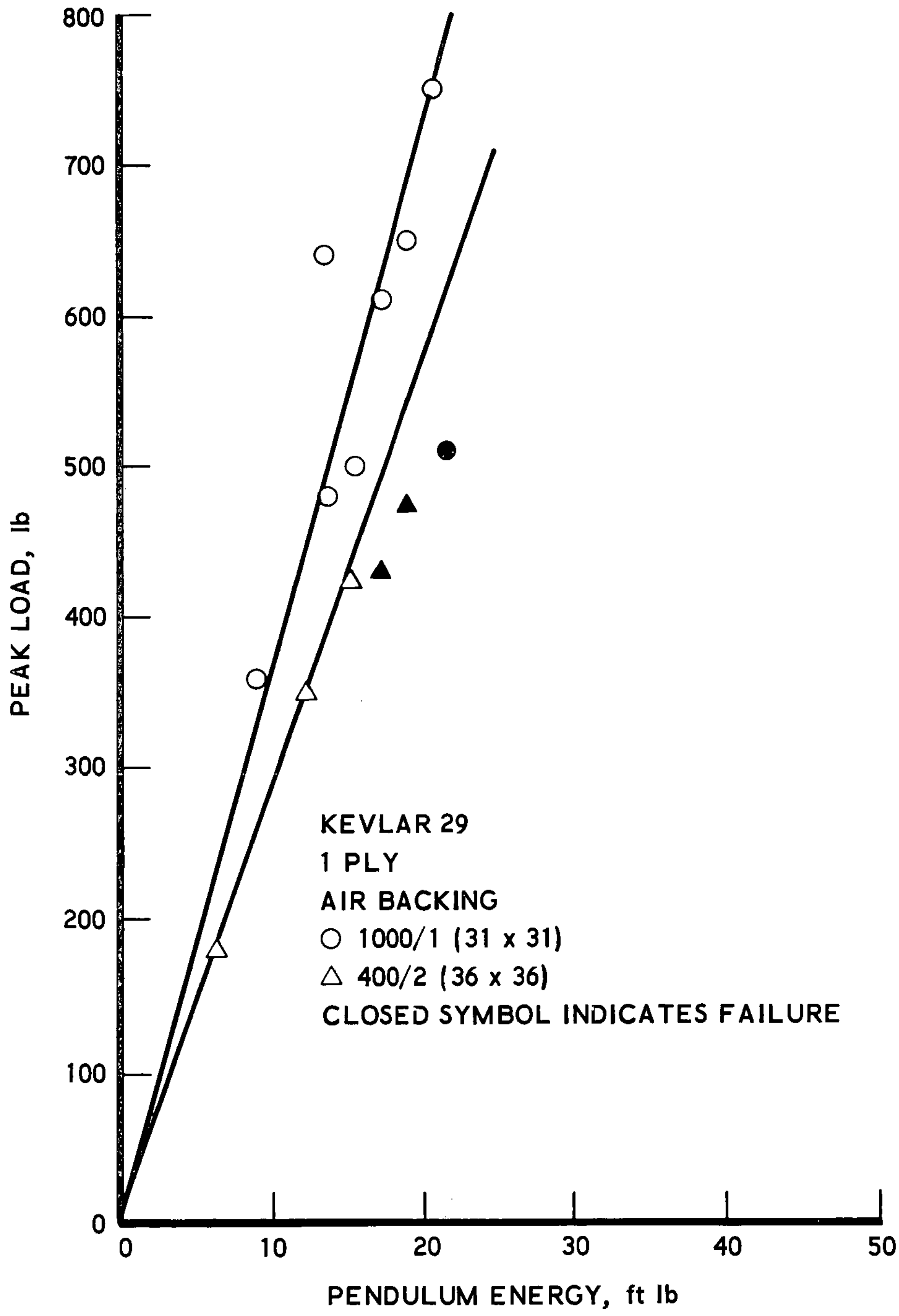


Fig. 23. Peak Impact Load vs Pendulum Energy

The lubrication mechanism was tested further ballistically. A 158-grain .38-caliber projectile at 800 ft/sec was found to completely penetrate seven plies of 400/2 (36 × 36) Kevlar 29 fabric when wet; only three plies of the dry fabric are required to defect the same threat. This problem has apparently been solved with the addition of a water-repellent coating and is discussed in more detail in the environmental test section. However, several points are noteworthy: (1) the long-time effects of water and humidity, even for the treated fabric, are not known; (2) both Edgewood Arsenal and Lawrence Livermore Laboratory used gelatin backing for all ballistic shots (although in humidity-controlled environments) and found no degradation in ballistic performance; and (3) anomalous results from the pendulum impact tests have usually occurred on days of high humidity. These observations suggest that the effect of humidity needs further investigation.

D. Discussion

The typical loading history for the air-backed, single-ply configuration (Fig. 19) is sinusoidal in character, with smooth loading and unloading phases that are reasonably symmetrical about the peak load. From Table III, the average period, i.e., total time of loading, is ~40 msec, corresponding to a frequency of 25 cps. In contrast, the clay-backed, single-ply configuration exhibits two sharply demarked loading phases, a nearly flat-topped peak load portion and two distinct unloading phases (Fig. 19). The average period is essentially the same as for the air-backed case. Finally, the gelatin-backed, single-ply configuration has a sinusoidal loading history that is similar in appearance to the air-backed case, except that the average period is about 50% longer; the average period is ~60 msec, corresponding to a frequency of 16.7 cps, i.e., lower than the air-backed configuration frequency.

In the air-backed tests, virtually all the pendulum energy is transferred to the fabric, since a negligible amount of energy is expended in displacing the air as the fabric deforms. Excluding the case of complete penetration, the interaction is highly elastic with little energy being absorbed through permanent deformation of the fabric (hysteresis in the Kevlar 29 fabric was not investigated). The elastically stored energy is returned to the pendulum, resulting in considerable pendulum rebound. In the gelatin-backed tests, the interaction is again highly elastic; there is virtually no permanent deformation of the gelatin until penetration of the fabric occurs, resulting in high pendulum rebound. Because the clay deforms plastically, energy is expended in forming the clay cavity, which results in lower peak loads.

For a given pendulum energy, approximately the same peak load is obtained for both air- and gelatin-backed tests, although the time to peak load is nearly 50% greater for the gelatin-backed test. Because of the plastic deformation of the clay (an energy-absorbing mechanism), the peak loads developed with clay backing are consistently lower than for the other two cases, although they occur at similar loading times as the air-backed configuration. The load produced in the indentor is due predominantly to tensile forces developed in the plane of the fabric. Evidently, relatively low forces are developed in the backing materials directly under the indentor at these loading rates; direct impacts into clay alone were insufficient to trigger the oscilloscope when set slightly under 50 lb. Although the forces are low, when summed over the entire membrane, the resultant pressure can greatly influence the stress field in the fabric and, thus, have a profound influence on the loading history. These differences in loading rates would be better understood if the graphical integration of the force-time (oscilloscope trace) curves were completed, i.e., the velocity and displacement with time would be known for the various cases.

From Figs. 20 through 22, a linear relationship exists between the peak load and the pendulum energy, regardless of number of plies or backing material. The slope of the curve for one ply appears to be slightly lower than for multiple plies (Fig. 20), indicating that two plies are not twice as efficient as one ply. The penetration load and corresponding pendulum energy (critical energy) from Figs. 20 through 22 are summarized in Table V as a function of number of plies and backing material. The data are also plotted in Figs. 24 and 25. It is seen that there is a linear relation between load-carrying capacity and number of plies for the air- and clay-backed cases. For the air-backed case, within the overall accuracy of the experiment, the penetration load increases by roughly 400 lb with the addition of each ply (Fig. 24). For the clay backing material, the penetration load increases by 500 lb with the addition of each ply after the first one (the penetration load for one ply is about 600 lb). In contrast, the variation of critical energy with number of plies is exponential (Fig. 25) and much steeper for the clay backing material, as would be expected because of the energy absorbed by the clay.

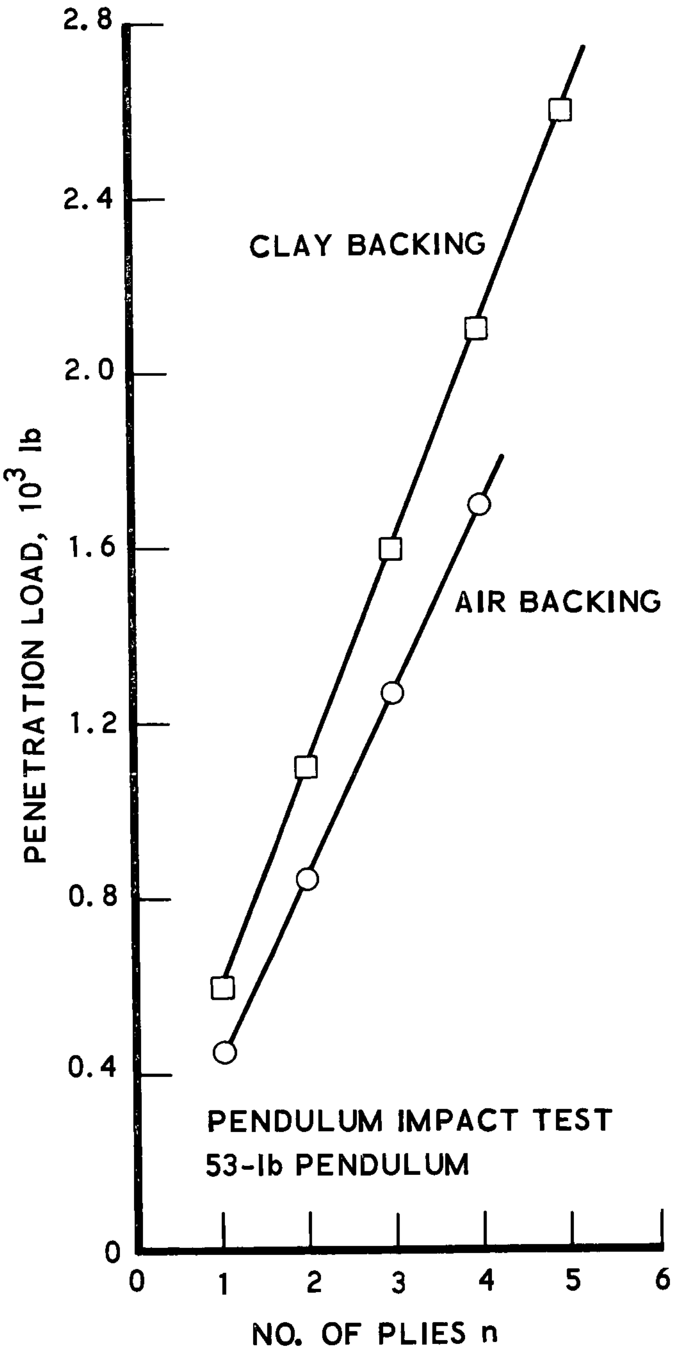


Fig. 24. Penetration Load vs Number of Plies

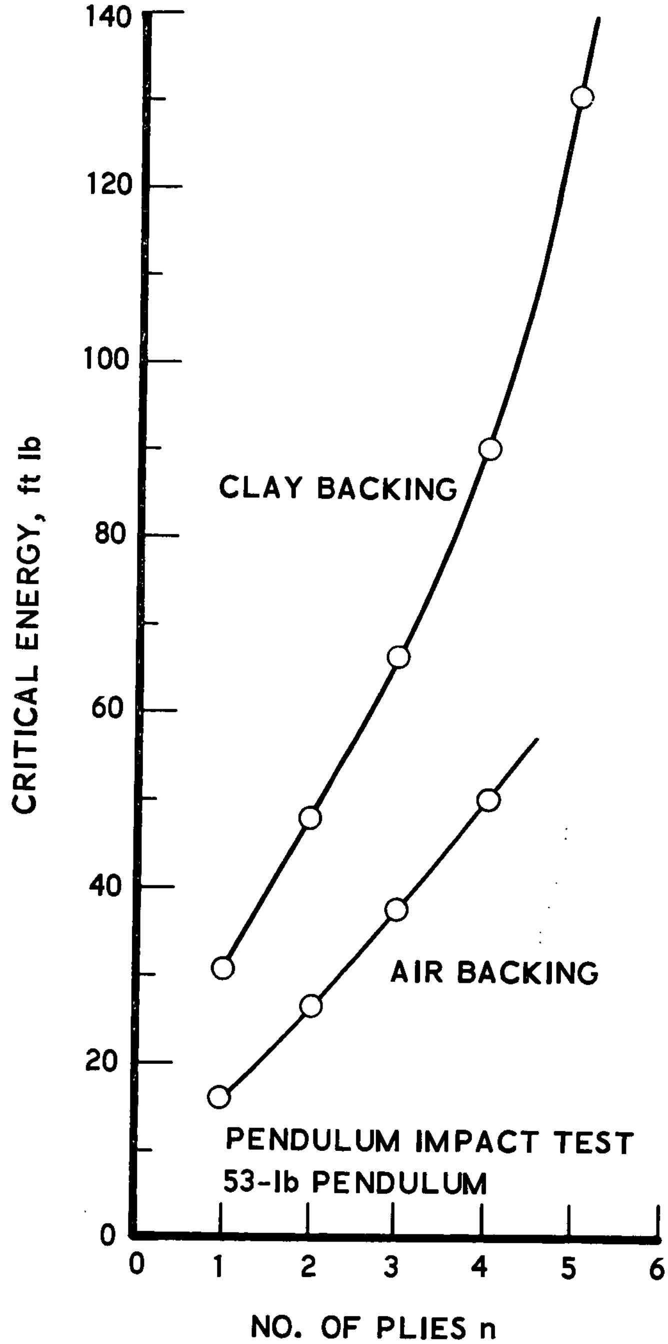


Fig. 25. Critical Pendulum Energy vs Number of Plies

Table V. Summary of Penetration Load P and Critical Energy Ec Under Pendulum Impact Conditions for 400/2 (36 × 36) Kevlar 29 Fabric

No. of Plies	Air Backing		Clay Backing		Gelatin Backing	
	P, lb	Ec, ft lb	P, lb	Ec, ft lb	P, lb	Ec, ft lb
1	450	16	600	31	500	18
2	850	27	1100	48		
3	1275	37	1600	66		
4	1700	50	2100	90		
5	---	---	2600	130		

Finally, from the difference in critical energy for penetration between the air-backed and the clay-backed cases, it would appear that between 44 and 50% of the energy is absorbed in the clay backing material for a given number of plies. The single-ply case again appears to be slightly different than the multiple-ply cases; the energy would appear to be almost equally partitioned between fabric and clay for one ply, whereas 44% of the energy goes into the clay for more than one ply. The data for the gelatin backing case are too sparse to draw significant conclusions but suggest that only a very small percentage (~10%) is taken up by the gelatin backing. This can be attributable to the highly elastic nature of the gelatin.

The few tests performed on a single ply of the 1000/1 (31 × 31) fabric are plotted in Fig. 23 together with the results for a single ply of the 400/2 (36 × 36). The 1000/1 fabric withstands much higher pendulum energies before failure for the single-ply air-backed case. The steeper slope for the 1000/1 fabric (higher peak load per given pendulum energy) indicates the fabric is responding more stiffly than the 400/2 fabric. These initial results on the 1000/1 indicate it to be superior to the 400/2.

CHAPTER IV. BALLISTIC RANGE CORRELATION TESTS

A limited number of ballistic range tests were carried out in which the same clay backing material was used as for the pendulum impact tests. This provided a means for correlating the laboratory data with bullet impact data. The clay provided a tool for measuring cavity volume and depth of penetration; cloth armor penetration resistance characteristics were also noted. This technique has also been used for evaluating such parameters as other weaves and the effects of washing and environmental conditions on a relative basis.

The majority of the tests were made with a 9-in.-square test sample size and a square test frame fixture that was positioned with the cloth material in contact with the unconfined clay backing material. Test range conditions made it impractical to use the heavy, 10-in.-diameter fixture from the pendulum impact apparatus for more than the minimum number of shots necessary to show that comparable results were obtained with the simpler fixture. The results of the ballistic range correlation tests are summarized in Table VI.

A. Correlation Factors

The correlation of the gelatin-backed ballistic data of Edgewood Arsenal (Table VIII) and Lawrence Livermore Laboratory (Table IX) with the clay-backed ballistic and pendulum impact data (Tables VI and VII) of The Aerospace Corporation requires a factor that can account for all the pertinent physical mechanisms of the interaction caused by the range of projectile

Table VI. Ballistic Range Correlation Test Results for 400/2 (36 × 36) Kevlar 29 Fabric Plastellina Clay Backing Material at $\rho = 1.5\ g/cm^3$

Test No.	No. of Plies	Bullet Caliber	Velocity v, ft/sec	Kinetic Energy, ft lb	Depth d, cm	Volume V, cm^3	MSF, J/cm
2-19-74							
40	7	.38	794	220	4.42	46.0	4.62
41	7	.22	1001	88.9	2.46	14.0	3.90
42	23	9 mm	1007	224	2.49	33.5	5.62
42a	18	9 mm	992	188	2.64	34.5	5.03
7-16-74							
1	7	.38	848	252	4.57	56.0	6.53
2			848	252	4.83	60.0	6.24
3			868	264	4.57	56.8	6.84
4			830	242	4.06	56.0	6.91
5			849	252	4.57	56.2	6.53
7			892	279	4.57	45.4	
7-31-74							
4	7	.38	887	277	4.52	47.3	7.30
8-14-74							
10	5	.38	864	264	4.80	67.0	7.58

Table VII. Pendulum Impact Correlation for 400/2 (36 × 36) Kevlar 29 Fabric Plastellina Clay Backing Material at $\rho = 1.5\ g/cm^3$ With 0.5-in.-diameter Steel Indentor (Shaped)

No. of Plies	Kinetic Energy, ft lb	Depth d, cm	Volume V, cm^3	MSF, J/cm^2
1	25.9	2.24	22.8	3.50
	29.2	1.93	21.5	5.20
2	25.9	1.68	16.8	4.88
	36.5	2.00	23.0	4.96
	43.9	2.11	22.0	5.41
	47.2	2.11	22.8	5.81
3	22.2	1.73	16.0	3.47
	43.9	1.85	16.8	5.98
	50.5	1.37	19.0	6.88
	58.0	1.98	19.0	6.96
	65.2	1.98	18.4	7.82
4	80.0	2.03	18.0	8.43
5	110	2.41	19.4	7.52
	127	2.57	23.0	7.78

energies. However, once established, such a correlation factor (which should be dependent upon the material tested) can be used to qualitatively judge other weave styles or possible improvements relative to the baseline fabric. Furthermore, valid correlation factors become indispensable to the formulation of more sophisticated mathematical models of the interaction.

Table VIII. Edgewood Arsenal Ballistic Range Correlation Test Results 400/2 (33 X 33) Kevlar 29 Fabric Backing Material at ρ = 1.0 g/cm

No. of Plies	Depth d, cm	Volume V, cm^3	Velocity v, ft/sec	Radius r^2, cm^2	Kinetic Energy, ft lb	MSF, J/cm^2
3	6.78	203	812	19.42	231	3.07
5	5.69	182	805	21.82	227	3.18
7	4.82	156	800	22.21	224	3.58
9	4.53	167	794	25.81	221	3.61
15	4.08	177	813	30.46	232	3.37
23	3.38	113	815	22.73	233	4.00
7	5.59	221	373	17.60	360	4.68
7	5.53	255	604	21.72	286	3.64
7	4.98	180	722	25.88	183	2.70
7	4.03	122	904	32.56	128	2.67
7	4.59	113	1013	27.91	115	1.94

Table IX. Lawrence Livermore Laboratory Ballistic Range Correlation Test Results for Gelatin-Backed Configuration for 400/2 (36 × 36) Kevlar 29 Fabric

No. of Plies	Depth d, cm	Volume V, cm	Velocity v, ft/sec	Interaction Time δ, msec	Kinetic Energy, ft lb	MSF, J/cm^2
3	5.20	3.70	761	0.80	203	4.41
5	4.75	3.45	841	0.80	248	5.23
7	4.75	3.30	827	0.94	240	4.47
9	3.85	3.30	810	0.78	230	5.37
15	3.15	3.10	854	0.60	256	6.75
7	3.75	3.40	565	1.02	112	3.07
7	3.85	2.90	670	0.84	157	4.13
7	4.15	3.40	863	0.76	261	6.07
7	4.20	2.85	977	0.66	335	7.64
7	2.30	2.35	1040	0.49	88.8	6.15
9	2.25	2.15	1033	0.54	87.6	5.78
15	1.65	2.45	1092	0.46	97.9	8.56
18	3.0	2.95	1132	0.52	327	8.73
23	3.8	3.10	1158	0.78	342	5.39

Several correlation factors were considered in the still rudimentary process of developing the membrane stiffness factor (MSF). The particular facets of the interaction that each served to bring out is briefly discussed in developing the MSF. Disregarding the case of penetration, the primary effects of armor thickness (ply number) occur in the initial 50 μsec of an impact (50 μsec corresponds to ~5% cavity formation). This conclusion results from Lawrence Livermore Laboratory data. Assuming the depth of penetration x to follow the relation

$$x(t) = \frac{v_A t}{1 + kt} \tag{22}$$

where v_A is a characteristic velocity (bullet, armor, and backing material), t is the time, and k a constant, we plot 1/x versus 1/t (Fig. 26). Three characteristic periods result: (1) an initial unsteady state ($t < 50$ μsec) in which the bullet loses up to ~50% of its velocity, (2) an intermediate steady state (50 μsec < t < 250 μsec) in which the characteristic velocity v_A remains constant, i.e.,

$$\frac{1}{x} = \left(\frac{1}{v_A}\right)\frac{1}{t} + \frac{k}{v_A} \tag{23}$$

and (3) a final state ($t > 250$ μsec) in which the whole system begins moving (bullet, armor, and gelatin block). From Lawrence Livermore Laboratory data, the empirical relation

$$v_A = \left(1 + n_p\right)^{-1/4} \tag{24}$$

was determined.

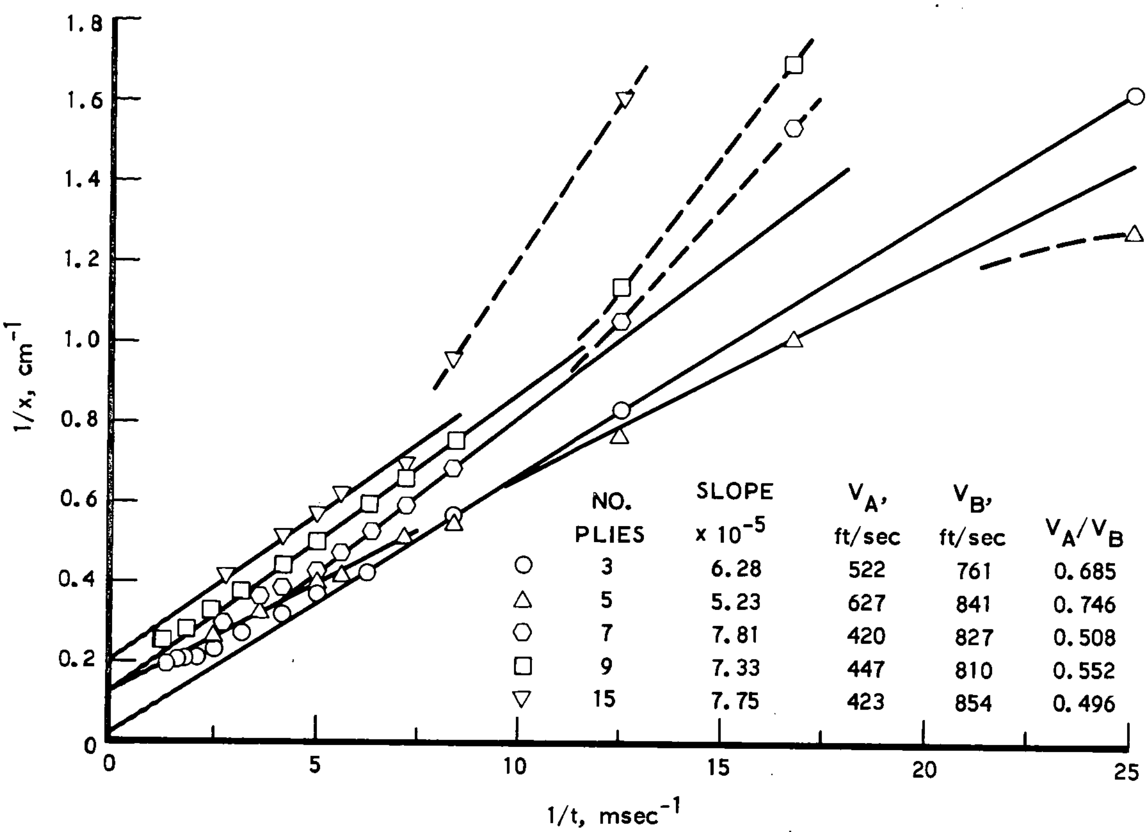


Fig. 26. Lawrence Livermore Laboratory Reciprocal Penetration vs Penetration Time for Gelatin-Backed Configuration

Once the kinetic energy of the bullet is formulated in terms of v_A, i.e.,

$$KE_B^* = \frac{1}{2} m v_A^2 \tag{25}$$

the remaining part of the interaction ($t > 50$ μsec) is found to be independent of ply number. This implies that the system is behaving as a membrane in which surface tension controls the interaction. With this basis, the membrane stiffness factor is

$$MSF = \frac{KE_B^*}{S_F - S_i} = \frac{KE_B}{\sqrt{1 + n_p}\ \Delta S} \tag{26}$$

where KE_B is the kinetic energy of the bullet prior to impact and S is the increase in surface area formed by the cavity, i.e., final minus initial area. This factor essentially represents the radial tension (dynes/cm) developed as the cone is formed.

The values calculated for MSF for the various data are listed in Tables VI through IX and plotted in Fig. 27 versus the kinetic energy of the bullet; v_A is equal to v_B for the pendulum impact (Fig. 19). All calculations assume a right circular cone for calculating ΔS. The four sets of data are found to group around three straight lines with a common intercept (zero). Thus, we define

$$MSF^* = \frac{C_1 KE_B}{\sqrt{1 + n \Delta S}} \tag{27}$$

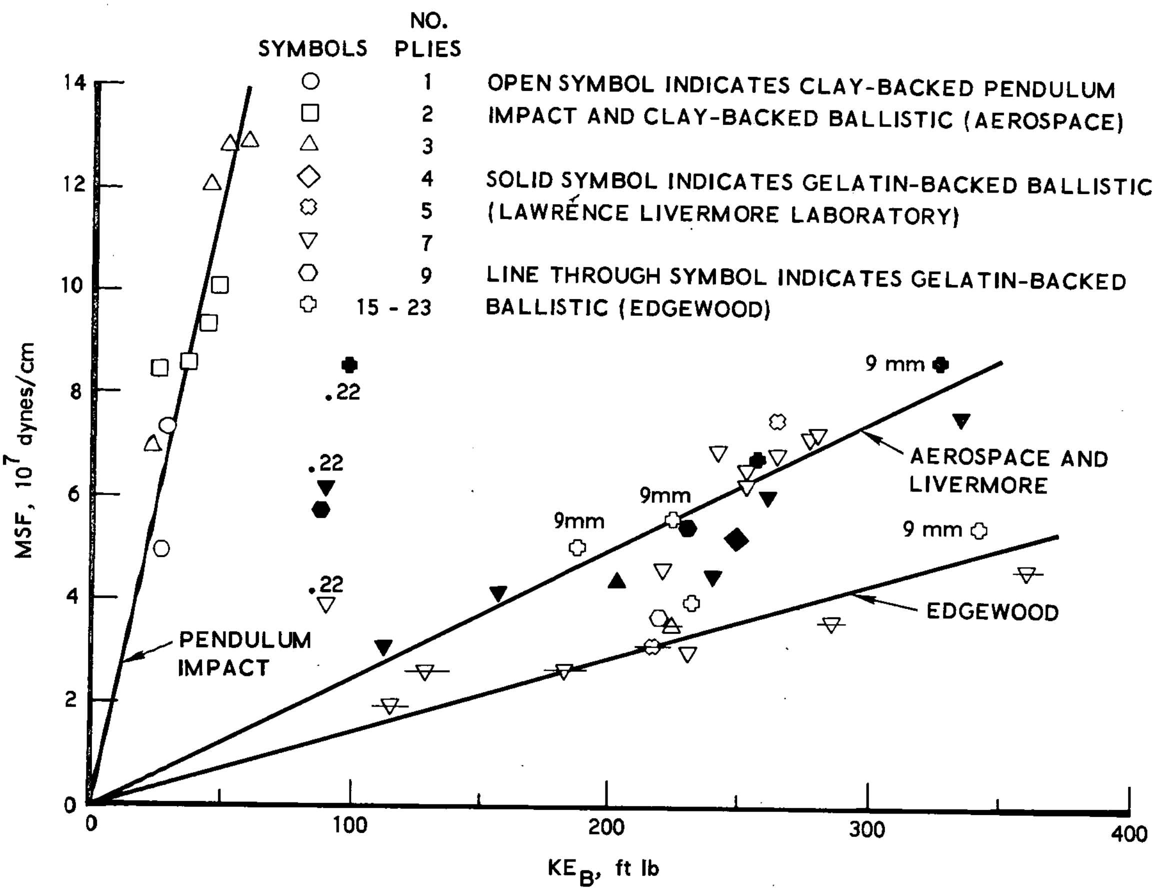


Fig. 27. Membrane Stiffness Factor vs Bullet Kinetic Energy for Eq. (26)

where C_1 is arbitrarily set equal to unity for the Aerospace pendulum impact data. Thus, we find C_1 equal to 17.3 and 9.5 for the Edgewood and Aerospace or the Lawrence Livermore Laboratory ballistic data, respectively. Disregarding the .22-caliber data, MSF^* is plotted versus KE_B in Fig. 28. Dis-slope of the straight line in Fig. 28 and the slope of the Aerospace pendulum impact data in Fig. 27 is $0.2 J\ cm^{-2}/J_6$.

B. Discussion

The constant C_1 is dependent on several parameters. Most important (from an empirical standpoint), it is dependent upon soft armor material behavior. Thus, once a baseline of data has been established by a given experimental procedure, such as pendulum impact or ballistic in gelatin, various materials can be qualitatively compared, i.e., 400/2 versus 1000/1. This partly explains the difference between the Edgewood and Lawrence Livermore Laboratory data; the Edgewood test incorporated the 400/2 33 × 33 pics/in. fabric. It should be further noted, however, that the parameters in the Lawrence Livermore Laboratory data were evaluated at 5% initial bullet velocity, whereas the Edgewood data were evaluated at maximum deformation or zero velocity; this possibly influences MSF to a greater extent than material properties.

The agreement between the Aerospace and Lawrence Livermore Laboratory ballistic data is, most probably, fortuitous. The Plastellina clay is suspected to have ~30% elastic recovery, which probably corresponds roughly to the volumes measured by Lawrence Livermore Laboratory. Also, the characteristic velocity v_A was evaluated from the Lawrence Livermore

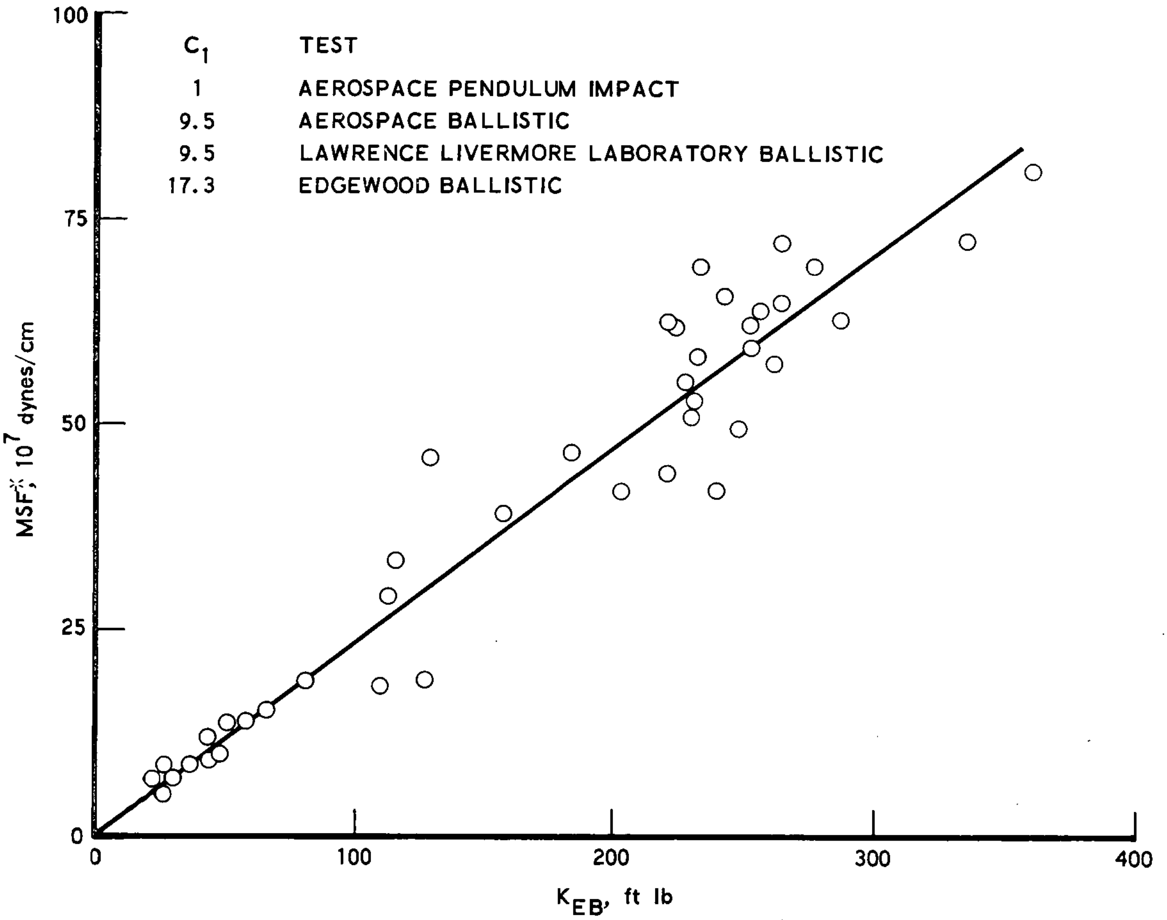


Fig. 28. Membrane Stiffness Factor vs Bullet Kinetic Energy for Eq. (27)

Laboratory data for gelatin-backed armor. We would expect v_A to differ somewhat for the clay-backed data. Possibly, these two effects have canceled each other.

The much steeper slope for the pendulum impact results is not too surprising for the following reasons: (1) in these tests the boundaries of the armor are clamped, which resulted in a much stiffer response; and (2) for an equivalent kinetic energy, the momentum is an order of magnitude higher and the velocity 2 orders of magnitude lower. The dependence of C_1 on the various parameters will be more fully understood when mathematical modeling of the interaction is accomplished.

The direct proportionality between the MSF and the kinetic energy of the bullet implies that the increase in surface area produced on impact is a material constant that is independent of ply number. This area increase is 5 cm^2 for the pendulum impact tests. Since the ballistic data were scaled by a factor of 17.3 for the Edgewood data and 9.5 for the Lawrence Livermore Laboratory or the Aerospace data, or both, the area increases for these data are 0.30 and 0.53 cm^2, respectively. The discrepancy between the pendulum impact data and the ballistic data results from basing the correlation factor MSF on only energy transfer rather than on momentum transfer. Immediately upon ballistic impact, the inertial characteristics of the membrane are brought into play, and these control the radial distribution of stress waves along the surface of the membrane. The constant C_1 is a measure of the ratio of the area to the front of the stress wave to the area directly impacted by the bullet.

These inertial effects are negligible in the pendulum impact, and thus solution of the membrane equations will lead directly to a prediction of both force-displacement and energy versus indentation area or volume. For the case of bullet impact, the inertial effects are very important. They can be modeled by incorporating the acceleration terms in the membrane equations. This solution would then lead directly to a prediction of depth and radius as functions of bullet kinetic energy and momentum, which can be correlated with the Lawrence Livermore Laboratory data.

CHAPTER V. CONCLUSIONS

The following conclusions have been drawn on the basis of the preceding assessment of the experimental data and the analyses.

Because of the extraordinarily high modulus (or stiffness) of the Kevlar 29 fibers, the fill fibers do not become crimped in the present weaving operation. For this reason, the fill fibers remain quite straight in the finished fabric, whereas the warp fibers are highly crimped because they must lay over and under the straight fill fibers. This weave configuration leads to extreme anisotropy (directional dependence) in the Kevlar 29 fabric.

Stretching the fabric in the fill direction results in a very high linear stress response to the stretch (or strain); since the fill fibers are already straight in the fabric, stretching in the fill direction is quite similar to stretching single, unwoven fibers. This further explains the zero Poisson's ratio (ratio of lateral contraction to longitudinal elongation). Since the warp fibers have little effect on the fill fibers, no lateral contraction occurs.

Conversely, when the fabric is stretched in the warp direction, considerable slack must be taken up, because of the heavy crimp, before the high modulus of the individual Kevlar 29 fibers comes into play. Thus, a relatively low initial stress response, associated with high strains (or elongation), is measured in the warp direction. Concurrently, as the warp fibers straighten because of the loading, the fill fibers must assume the crimp initially carried by the warp fibers. The induced crimping of the fill fibers as the warp fibers are straightened results in extremely high lateral contraction of the fabric. These two extreme behaviors in the warp and fill directions explain the rather diverse failure mechanisms in the pendulum impact and ballistic tests.

The fill fibers carry the majority of the load because of their low elongational (strain) capability. When locally loaded with a rigid indentor, such as the pendulum-impact or 9-mm jacketed bullet, failure is initiated in the fill fibers. However, inspection of fabric failure when impacted with a soft, deforming indentor (lead bullet) indicates that failure is usually initiated in the warp fibers. The following mechanism is proposed to explain this discrepancy. A lead bullet impacting the Kevlar 29 armor is deformed into an elliptical shape with its major axis in the warp direction, i.e., the direction of least resistance. As the bullet deforms in the warp direction, the fill fibers are forced to the sides of the bullet. This causes the warp fibers to be highly loaded, which results in failure.

The anisotropic stress-strain response of the baseline Kevlar 29 fabric has been fully characterized and incorporated into an analytical expression. This expression, when coupled with a proper armor impact model, will yield the stress distributions, forces, and displacements of the overall ballistic interaction. Once the interaction is properly modeled, optimization of the soft armor to minimize a particular reaction, such as blunt trauma and penetration, is easily effected. Obviously, failure criteria will have to be established in order to optimize the penetration characteristics of the fabric.

The membrane stiffness factor (MSF) correlates the pendulum impact data with the ballistic data within a numerical constant. This constant is dependent upon both material (or fabric) properties and the dynamics of the interaction. If the tests conditions are held constant, i.e., the dynamics of the test, the material dependence of this constant should be measurable. If sensitive to the material properties, the MSF should permit discrimination between armors of different weaves and deniers. The inertial dependence of this constant will be determined when an analytical armor impact model is developed.

Studies of energy partitioning indicate that as much as 45 to 50% of the impact energy could be going into the backing material in the pendulum impact tests, on the basis of clay-backing test data. Data on gelatin-backing response are not sufficient to draw any significant conclusions, although the one data point available would suggest a lower percentage (~10%) being absorbed by the gelatin. It is not known which material more correctly simulates the response of the human body.

CHAPTER VI. RECOMMENDATIONS

As a result of the phenomenological study, areas requiring additional investigation have been identified. The present Kevlar 29 fabric exhibits extreme anisotropy because of the current weaving technique, i.e., transverse mechanical loading of the fabric is supported chiefly by the virtually uncrimped fill yarns (the warp yarns are highly crimped, which gives them a high strain or elongational capability). A woven fabric that has approximately equal crimp in both the warp and fill directions, without sacrificing fabric density (pics/in.), should greatly improve penetration resistance and blunt trauma alleviation. A comprehensive study of weaving parameters, such as initial tension effects of twist and lubrication, should be carried out.

The pendulum impact tests showed two plies of fabric to display less than twice the penetration resistance of a single ply, i.e., armor response does not increase linearly with ply number. Preliminary testing implies that simple quilting of the multiple-ply configuration enhances the efficiency of multiple plies. A detailed study of quilting, angular orientation of adjacent plies, and similar techniques should be carried out as a means of improving the efficiency of the multiple-ply configuration. This effort should include both pendulum impact and ballistic testing.

Composite materials permit the best features of different materials to be tailored into a single design for meeting specific requirements. For instance, the flexible Kevlar 29 fabric was chosen for its comfort and inconspicuousness; consequently, it lacks the protective capability inherent in the ceramic and rigid composite armors, which is necessary for alleviation of localized blunt trauma through dissipation and spreading of the energy and momentum. The advantages of both types of armor (flexible, comfortable fabric, and rigid, energy-dissipating ceramics) can be realized in a single composite armor through the proper application of time- or rate-dependent materials.

All elastomers (or rubbers) exhibit rate-dependent behavior (rubberlike to glasslike behavior), depending upon the temperature and time regime of deformation. Before compounding a rubber coating to yield the desired response, however, the feasibility or benefits of such a composite should be investigated. This can be accomplished by preparing samples that have the two extreme properties. That is, fabric specimens can be coated with an existing rubber coating (polyurethane) to ascertain the maximum rubbery coating permissible while still retaining the flexibility required for a comfortable garmet. The other extreme can be obtained by applying an epoxy or polyester coating to determine the additional protection such a coating would offer under high-rate loading. If these results prove to be beneficial, the necessary rate-dependent coating could then be compounded, which would yield the two extreme properties over the range of time loading between ordinary wearing and the ballistic interaction.

An area completely overlooked in the present study is that of the exotic weaves. Multidimensional weaves (three dimensional and triaxial) have received substantial impetus under reentry-vehicle hardening programs in DoD because of geometric dispersion benefits in dissipating shock waves. Both the three-dimensional and triaxial weaves should be qualitatively compared with the equivalent (density basis) two-dimensional weave on a penetration resistance and blunt trauma basis.

It has been established that water significantly degrades the penetration resistance capability of the Kevlar 29 fabric. The effect of humidity has not been determined and can possibly be equally as detrimental. Although this problem has apparently been solved through the application of the Zepell coating, it is not known whether private industry will continue use of the Zepell coating, nor are the effects of environmental aging on the Zepell coating known. Thus, a study should be directed toward gaining an understanding the effect of humidity on the fabric.

A major part of the overall soft-armor program has involved animal testing directed toward the effect of blunt trauma on living organs. To date, it has not been possible to correlate these results with humans because of a general lack of knowledge of the ballistic interaction processes. Similarly, for the lack of an adequate model, additional animal testing will be required as new armor materials are introduced, e.g., 1000 denier, 31 × 31 pics/in. The development of an armor impact model would solve many of these problems as the energy and momentum transfer associated with the bullet, armor, and backing would be predictable. Thus, the wound characteristics of a particular organ could be associated with known loading conditions. These loading conditions could then be predicted for any armor system, i.e., different weaves, ply orientation, and composite materials. A continued effort would be directed toward the analytical solution of a membrane subjected to large concentrated loads. This solution would predict the static indentor and pendulum impact results. The final step would involve prediction of ballistic response coupled with various backing materials.

APPENDIX B

AEROSPACE CORPORATION SPECIFICATION LEDG 7906-1

WEAVING SPECIFICATION FOR KEVLAR-29 FABRIC FOR LIGHTWEIGHT BODY ARMOR

LEDG 7906-1 KEVLAR-29 WEAVING SPECIFICATION
CLOTH, ORGANIC FIBER, HIGH MODULUS FOR BALLISTIC GARMENTS

1.0 SCOPE

1.1 Form: This specification covers fabrics woven from high modulus Kevlar-29, multi-filament yarn having a specified minimum ballistic resistance.

1.1.1 Types: Type 1 is style 100 and Type 2 is style 120. Both types are delineated in Table 1.

2.0 APPLICABLE DOCUMENTS AND SPECIFICATIONS

2.1 ASTM Publications: Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.

ASTM D123	Definition of Terms Relating to Textile Materials
ASTM D1682	Breaking Load and Elongation of Textile Fabrics
ASTM D1777	Measuring Thickness of Textile Materials
ASTM D1910	Construction Characteristics of Woven Fabrics
ASTM D737	Air Permeability of Textile Fabric
ASTM D579	Breaking Load and Elongation of Textile Fabrics

2.2 Federal Specifications:

PPP-P-113	Packaging and Packing of Synthetic Fiber Fabrics
CCC-T-191	Textile Test Methods

2.3 Military Standards

MIL-Std-105	Sampling Procedures and Tables for Inspection by Attributes
MIL-Std-662	Ballistic Acceptance Test Method for Personal Armor Material

3.0 REQUIREMENTS

3.1 Bid Sample and Laboratory Report Approval: Unless otherwise specified at the time of submission of a bid, the bidder may submit to The Aerospace Corporation a sample of the fabric with a certified copy of a recent laboratory report covering the fabric which he proposes to deliver in order to demonstrate weaving capabilities.

3.1.1 First Article: This specification contains provision for first article inspection and approval (see paragraph 4.3.2.4 and 8.4). A sample of 10 yards from the beginning of the production run will be tested according to the tests specified herein before approval of go-ahead on remaining yardage (untreated sampled will be tested.

3.2 Material

3.2.1 Yarn: The warp and filling yarn shall be Kevlar-29, DuPont Type 964, multi-filament yarn and shall meet the requirements of Table III.

3.2.2 Color: The color of the finished fabric shall be natural as produced from the yarn provided by the manufacturer.

3.2.3 Physical Requirements: The finished cloth shall conform to the physical requirements specified in Table I when tested as specified herein.

3.2.3.1 Weave: The weave shall be a 1 by 1 plain weave with one end weaving as one and one pick weaving as one.

3.2.3.2 Reeding: The warp yarn shall be reeded with not more than 2 ends per dent.

3.2.3.3 Twisting: If necessary, to insure better cohesion of the yarn, the contractor shall use dampened pad, using water or poly vinyl alcohol (PVA) applied to the yarn prior to entering the twisting mechanism.

3.2.3.4 Finish: The finished cloth shall be thoroughly scoured and shall be processed according to meet the ballistic requirements of the specification. The supplier shall certify that no bleaching or loading material has been applied in the processing of the cloth without specific prior approval of The Aerospace Corporation.

3.2.3.5 Length and Put-Up: The cloth shall be furnished in rolls 80 to 120 yards. Each roll shall contain not more than two pieces and no single piece shall be less than 40 yards. Each length shall be put in full width rolls as specified in PPP-P-1133.

3.2.3.6 Workmanship: The finished cloth shall conform to the quality and grade of product established by this specification. If the occurence of defects exceed the level specified in paragraph 3.4.1, the resulting fabric shall not be acceptable.

3.2.3.7 Water Repellent: After the fabric has been scoured, a treatment of Zepel D produced by DuPont shall be applied. An equivalent treatment may also be utilized on approval of The Aerospace Corporation. The treatment shall be applied in the following manner:

Formulation

Product	% Product on Fabric
Zepel D (15% Solids)	4.0
Nalan W (25% Solids)	4.0

The fabric shall be treated by passing the cloth through the above mix twice (2 dips) and squeezing the fabric once (1 Nip) between rubber rollers. The squeezed fabric shall then be passed onto a dip tenter frame which carries the fabric through the drying oven. Oven temperature shall be $400^{\circ}F \pm 10^{\circ}F$ for 1-1/4 minutes. After oven curing the fabric shall receive an after wash in an overflow of water at $170^{\circ}F$ to remove uncured and unreacted materials. Squeeze dry and place in a drying oven at $400^{\circ}F$ for 1-1/4 minutes to complete the drying cycle.

The finished coating shall be tested for resistance to water at a spray rating of 100, method 5526 of Fed. Spec CCC-T-191.

3.3 Properties

Shall be as specified in Table I. Tests shall be made on the product supplied and in accordance with test methods specified. herein.

3.4 Quality

The product shall be uniform in quality and condition, clean, smooth and free from foreign material and from specific imperfections in the fabrication. Only fabric within the specific imperfection allowables defined below will be accepted.

3.4.1 Imperfections: In any 100 yards (91.4 m) of fabric supplied, there shall be no more than the equivalent of 10 major imperfections (2 minors = 1 major) based on the following imperfection classifications: Fabric will not be accepted with greater than 10 major imperfections. Any single major imperfection greater than 1 yard in extent will be cause for rejection.

Imperfection	Description & Limitation	Classification
Baggy; ridgy or wavy cloth	Clearly noticeable	Major
Crease	Hard, embedded, and folded over on self	Major
Cut or Tear	Clearly noticeable in any direction, any size	Major
Hole	Clearly noticeable, any size	Major
Spots, Streaks or Stains	Clearly noticeable 2 in. (50.8 mm) or more in combined direction.	Major
	Clearly noticeable less than 2 in. (50.8 mm) in combined direction	Minor
Smash	2 in. (50.8 mm) or more in combined directions.	Major
	Less than 2 in. (50.8 mm) in combined directions.	Minor
Runs (broken or missing picks or ends)	Clearly noticeable for each 2 in. (50.8mm) in length in combined directions.	Major
Floats, Single and Skip	1 in. (25.4 mm) or more in combined directions	Major
	Less than 1 in. (25.4 mm) in combined directions	Minor
Floats, Multiple	0.5 in (12.7 mm) or more in combined directions	Major
	Less than 0.5 in. (12.7 mm) in combined directions	Minor
Light Place, Fill Direction	Over 1/8 in. (3.17 mm) in width	Major
Selvage Defects	Cut or torn	Major

3.4.2 Identification of Imperfection: All imperfections will be flagged at the selvage area and properly identified.

3.5 Tolerances

3.5.1 Width: Unless otherwise specified, the width shall be 48" ± 1/2 in (± 12.7 mm).

3.5.2 Weight: Unless otherwise specified, the weight shall conform to the following limits:

Normal Weight (oz per sq yd)	Permissible Variation
over 7.00	± 1/4 oz per sq yd.

3.5.3 Fabric Count:

3.5.3.1 Warp: The average count of warp ends shall be within the limits of -1/2,+ 1 ends from the normal count, listed in Table 1.

3.5.3.2 Fill: The average count of filling picks shall be within the limits of -1/2,+ 1 pick from the normal count listed in Table 1.

3.5.4 Air Permeability: Permeability measurements shall be made in accordance with ASTM D737 and must meet the requirements in Table 1.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection: Unless otherwise specified, the contractor is responsible for the performance of all inspection requirements as specified herein. The contractor may use his own or any other facility suitable for the performance of the inspection requirements, unless disapproved by The Aerospace Corporation. The Aerospace Corporation reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure that finished cloth meets the prescribed requirements.

4.1.1 Certificate of Compliance: Where certificates of compliance are submitted the customer reserves the right to check test such items to determine the validity of the certifications.

4.2 Classification of Tests: Tests to determine conformance to all technical requirements of this specification are classified as acceptance or routine control tests.

4.3 Inspection: Sampling for inspection shall be performed in accordance with MIL-Std-105, except where otherwise indicated.

4.3.1 Lot: A lot shall be all material produced in a single production run under the same fixed condition and submitted for inspection at one time.

4.3.2 Frequency of Sampling

4.3.2.1 100% Inspection: Each roll in the lot shall be visually examined 100% on both sides. All defects as defined in (3.4.1) shall be scored and assigned imperfection scores as listed in (3.4.1).

4.3.2.2 Fabric Tests: Sample size for fabric test shall be as follows:

Lot Size - Yard	Sample Size - Yards
Up to 3,000	2
3,000 to 15,000	5
Over 15,000	10

(Number of samples may be increased if necessitated by test results).

4.3.2.3 Ballistic Tests: Samples, as specified in 4.5.1(a), of fabric from production run shall be tested to demonstrate ballistic resistance.

4.3.2.4 First Article Inspection: The preproduction sample submitted in accordance with paragraph 3.1.1 shall be visually inspected and tested in accordance with paragraph 4.5.

4.3.2.5 Overall Examination: The fabric shall be examined for extensive, general, or overall defects. Any roll containing any of the following defects shall be rejected:

a. width not within established tolerance

b. net length less than indicated on ticket

c. incorrect deductions for defects strung by the contractor, as indicated on piece ticket

4.4 Approval

4.4.1 Sample material shall be approved by The Aerospace Corporation before material for production use is supplied, unless such approval is waived. Results of tests on production material shall be essentially equivalent to those on the approved sample.

4.4.2 The contractor shall use ingredients, manufacturing procedures, processes and methods of inspection on production material which are the same as those used on the approved sample material (3.1.1). If any change is necessary in ingredients, in type of equipment for processing, or in manufacturing procedures which could affect quality or properties of the materials, the contractor shall submit samples for reapproval unless the customer grants written approval after review of a detailed statement of materials and processing used on the approved sample and those proposed. No production material shall be made by the revised procedure prior to receipt of approval of such procedure.

4.5 Test Method: Tests to determine conformance to this specification shall be as follows:

Permeability	ASTM 737, Air Permeability of Textile Fabric (suggest using Gurley 4307 instrument for testing)
Weight	ASTM D1910, Small Sample Method
Nominal Thickness	ASTM D1777, ASTM D-579
Fabric Count	ASTM D1910
Breaking Strength	ASTM D1682, ASTM D-579
Spray Rating	Fed. Spec CCC-T-191, Method 5526

4.5.1 Tests: The methods of testing specified shall be followed. Except for ballistic resistance the values specified in Table 1 apply to the results of the determination made on a sample unit for test purposes as specified in the applicable test method. Except for ballistic resistance, the lot shall be unacceptable if one or more sample units fail to meet any requirements specified. For ballistic resistance; the lot shall be unacceptable if any test fails to meet the ballistic resistance requirements (see 4.5.2). The sample unit for test purposes shall be as follows:

a. Ballistic Tests: Four cuts of 12 inches and full width of the finished cloth originating from a different roll.

b. For all other tests, one cut 2 feet long and full width of the finished cloth originating from one of the four pieces from which the sample unit of the ballistic test is drawn. Each individual cut comprising sample (a) and (b) shall be marked to indicate supplier's piece, lot and roll number. The lot size shall be expressed in units of 1 linear yard. The sample size shall be as specified in 4.3.2.2.

4.5.2 Ballistic Resistance Tests

4.5.2.1 Test: The test shall be conducted in accordance with the Ballistic Resistance and Police Body Armor NILECJ-Std-0101.00 or the following procedure:

4.5.2.1.1 Test Panels: The four cuts comprising the sample unit for ballistic test (4.5.1(a)) shall be cut into 12 inch x 12 inch sections. The sixteen cloth specimens thus obtained shall make up the test panels for testing. Seven plies will be used for the 38 caliber tests and seven plies for the 22 caliber tests.

4.5.2.1.2 Test Projectiles: The test projectiles shall be:

a. .38 caliber 158 gr commercial load capable of achieving 800 feet per second (fps) minimum velocity.

b. 22 caliber 40 gr commercial load capable of achieving 1000 feet per second (fps) minimum velocity.

4.5.2.1.3 Test Articles:

a. 38 caliber 4-1/2 inch barrel, Smith & Wesson or equivalent

b. 22 caliber 6.0 inch barrel, Smith & Wesson or equivalent

4.5.2.1.4 Velocity: Velocities shall be measured by using a standard chronograph as specified in MIL-Std-662.

4.5.2.1. Target Backing: The armor target material shall be comprised of clay blocks approximately 12 inch x 12 inch x 6 inch deep. Type of clay is Plastellina Grade I, manufactured by Roma Plastellina, 304 W. 42nd St., New York, N.Y. or equivalent material with the same density.

4.5.2.1.6 Target Distance: The distance between the test articles and targets shall be approximately ten feet.

4.5.2.1.7 Number of Impacts: Six impacts will be made in an unsupported area of each test panel.

4.5.2.1.8 Fair Impact: An impact is considered fair when a projectile strikes the unsupported area of the armor test panel at least 2 inches from any previous impact and at least 2 inches from a supported area without causing complete penetration of any given projectile.

4.6 Resampling and Retesting: If any specimen used in the above tests fails to meet the specified requirements, disposition of the fabric may be based on the results of testing three additional specimens for each original nonconforming specimen. Failure of any retest specimen to meet the specified requirements shall be cause for rejection of the fabric represented and no additional testing shall be permitted. Results of all tests shall be reported.

5.0 PREPARATION FOR DELIVERY

5.1 Identification

5.1.1 Rolls: Each roll of fabric shall have attached a tag showing the manufacturer's name or trademark and the phrase "CLOTH, ORGANIC FIBER, HIGH MODULUS, STYLE 100 OR STYLE 120".

5.1.2 Packages: Each package shall be permanently and legibly marked to give the following information:

Cloth, Organic Fiber, High Modulus, ____________ Style Fabric
Yardage ____________________
Width ____________________
Purchase Order Number ____________________
Manufacturer's Identification ____________________
Lot ____________________
Weight of Package ____________________

5.2 Packaging

5.2.1 Packaging shall be accomplished in accordance with Fed-Std-PPP-P-1133 in such a manner as to ensure that the fabric, during shipment and storage, will be protected from exposure to moisture, weather, or any normal hazard.

5.2.2 Packages shall be prepared for shipment in accordance with commercial practice to assure carrier acceptance and safe transportation to the point of delivery. Packaging shall conform to carrier rules and regulations applicable to the mode of transportation.

6.0 NOTES

6.1 Definitions: For definition of terms, refer to ASTM D123.

6.2 Intended Use: The Kevlar-29 ballistic cloth covered by this specification is intended for use in the fabrication of lightweight protective body armor for public officials and law enforcement personnel.

6.3 First Article: When a first article is required it shall be inspected and approved under the appropriate provisions of the specifications. The first article should be a preproduction sample as specified in 3.1.1. The first article should consist of ten (10) yards of the unfinished fabric. The Aerospace Corporation will inspect and approve the preproduction sample in accordance with the requirement of Paragraph 4.0 hereof.

TABLE I

CONSTRUCTION OF WOVEN KEVLAR-29

Style	Yarn Count per Inch (25.4 mm)		Yarn Type (1)		Weave	Twist (2)		Weight	Breaking Load		Elongation %		Air Permeability
	Warp (3)	Fill	Warp	Fill		Single	Ply	Oz per Sq Yd	Lbs/1 in. Width Min. Warp	Lbs/1 in. Width Min. Fill	Warp	Fill	CU. FT/MIN(Max)
100	36	36	400-2	400-2	Plain	0	3Z	8.00 ± 0.25	1150	1500	11.0 +5 -0	4.0 +2 -0	30
120	31 (4)	31	1000-1	1000-1	Plain	0 (5)	D	8.50	1200	1500	10.0 ± 0.5	5.0 ± 0..	10

1. Denier - number of plies
2. Twist tolerance = 3Z ± 0.25 turns per inch
3. Use a #18 reed for 36 ends per inch with 2 ends per dent
4. Uses a #31 reed for 31 ends per inch with one end per dent
5. Use normal manufacturing twist

TABLE II - TEST METHODS

Characteristics	Requirement Paragraph	Test Method
Yarn		
Denier	3.2.1	1/
Ply	3.2.1	1/
Twist (turn per inch)	3.2.1	1/
Reeding	3.2.3.2	1/
Finish	3.2.3.4	1/
Yarn Breaking Strength		
Warp	3.2.1	ASTM D-1682 and ASTM D-579 [1]
Fill	3.2.1	ASTM D-1682 and ASTM D-579 [1]
Elongation	3.2.1	ASTM D-1682 and ASTM D-579 [1]
Weight	3.5.2	1/
Yarns per Inch		
Warp	3.5.3	1/
Fill	3.5.3	1/
Air Permeability	3.5.4	ASTM D-737
Weave	3.2.2	Visual
Ballistic Tests	4.5.1	1/
Spray Test	3.2.3.7	CCC-T-191, Method 5526

1/ Unless otherwise specified, a certificate of compliance shall be submitted and will be acceptable for the stated requirements.

1 Modified grip tests using thin aluminum or cardboard attachments to the gripping area of the specimen.

TABLE III

Kevlar-29 400 Denier Yarn Properties

	Density	No. of Filaments	Diameter of Filaments	Denier per Filament	Elongation to break	Tensile strength[1]	Modulus
Type I	1.44 gm/cc	267	0.00047 in	1.5	$4\%\ ^{+2}_{-0}$	400,000 psi	6×10^6 psi
Type II	1.44 gm/cc	666	0.00047 in	1.5	$4\%\ ^{+2}_{-0}$	400,000 psi	6×10^6 psi

(1) dry yarn strength

APPENDIX C

AEROSPACE CORPORATION SPECIFICATION LEDG 7906-2

FABRICATION SPECIFICATION FOR BALLISTIC PROTECTIVE UNDERGARMENT

1.0 SCOPE AND CLASSIFICATION

1.1 Form: This specification covers the design of, and requirements for fabricating a ballistic protective undergarment designated for wear by public officials and law enforcement personnel.

1.2 Classification: The undergarment shall be of two types in the sizes or styles required as shown in Figure 1.

2.0 APPLICABLE DOCUMENTS AND SPECIFICATIONS

The following documents form a part of this specification to the extent specified herein. These documents are also to be used for information related to the fabrication of the garments.

2.1 ASTM Publications: Available from American Society for Testing and Materials, 1916 Reece Street, Philadelphia, Pennsylvania 19103:

ASTM-D-1683-68	Textile Materials
ASTM-D-123	Definition of Terms Relating to Textile Materials

2.2 Federal Specification Publications: Available from Department of Defense (DFSIC), Gaithersburg, Md.

Federal Std 191	Textile Test Methods
Federal Std 751	Stitches, Seams and Stitching
JJ-U-513	Undershirt, Man's Cotton, Quartersleeve
JJ-W-155	Elastic
VT=285	Thread, Polyester Cotton Class 1B Cotton
PPP-B-636	Fiberboard Box, Shipping.

2.3 Military Standards Publications: Available from Department of Defense (SFSIC), Gaithersburg, Md.

MIL-Std-105	Sampling Procedures and Tables for Inspection by Attributes
MIL-T-5038	Tape, Textile and Webbing, Textile, Reinforcing
MIL-F-21840	Fastener, Tape, Hooks and Pile, Nylon - 1" width

2.4 Other Specifications

Aerospace Corporation Specification 7906-1	Weaving specification for Kevlar-29 fabric for lightweight body armor.

3.0 REQUIREMENTS

The requirements contained herein are for a protective undergarment which will serve the needs of the law enforcement community. Emphasis shall be placed on resistance to ballistic penetration, without the sacrifice of mobility, lightweight, or comfort.

3.1 First Article: The contractor shall furnish two (2) garments each of two (2) styles for first article inspection and approval before production of final garments. The first article shall consist of completed garments which will be maintained at The Aerospace Corporation for a quality standard.

3.2 Material

3.2.1 Protective Material: The protective material to be used in the garment shall be 7 plies of Kevlar-29 fabric, Style 120.

3.2.2 Shell: The shall or outer cover shall be constructed of cloth cotton filling satin, 60 x 90 (min.) texture, 3.5 oz/yd^2 (min), 25 lb/min warp and 50 lb/min fill breaking strength. Fabric shall be bleached, mercerized and calendered. Color shall be white. Test method 5100 of FED. STD. 191 shall be used to determine breaking strength.

3.2.3 Tail: The tail shall be constructed of 100% cotton per Federal Specification JJ-U-513.

3.2.4 Webbing: The webbing shall be constructed of 1" nylon tape, type III, MIL-T-5038.

3.2.5 Elastic: The elastic material shall be 1" wide natural color per Federal Specification JJ-W-155.

3.2.6 Thread: The thread shall be a water repellant polyester cotton per Federal Specification VT-285 Class 1B.

3.2.7 Velcro: Velcro fastener, tapes, hook and pile, nylon white 3054, 1" wide, type I, class 1 of specification MIL-F-21840 (fastener, tapes, hook and pile)

3.3 Patterns: The master patterns will be furnished by The Aerospace Corporation. The patterns shall not be altered in any way and are to be used as a guide for cutting the contractor's working patterns.

3.4 Design: The undergarments will be of two design styles. Style 1 undershirt has ballistic material on the sides of the garment providing complete torso protection. Style 2 undergarment does not have ballistic material on the sides. Design of these undergarments shall be as shown in Figure 1.

3.5 Manufacturing Operations: In manufacturing the garments the following details shall be observed.

3.5.1 Cutting and Spreading: The Kevlar fabric shall be laid up in plies in such a manner as to maximize yield and minimize waste. The spreading procedure shall be performed in such a manner as to avoid distortion of the fabric and eliminate stretching or bulging of the finished garment. The spreading procedure can be accomplished by a patting procedure or by mechanical process. The cutting procedure shall be performed to assure that there is no unravelling or fraying-out of the edges or rough cuts. To assure proper fitting and neatness, a minimum of 7 plies (the number of plies contained in 1 garment) should be cut at the same time. The number of plies to be cut must always be in multiples of seven (7).

3.5.2 Stitches, Seams and Stitching: The contractor shall adhere to seam and stitch types which are defined in Fed. Std. 751. The 7 plies of Kevlar-29 shall be sewn together by 1 row of stitching 1/2" from the outer edge, using thread, polyester, size E, 7 to 11 stitches per inch, type 301. The sewing of the 7 plies together eliminates slipping or any other movement of the ballistic material. In addition, the 7 plies of Kevlar fabric of the back panel shall be held together by 3 parallel rows of stitching extending from the neck end of the garment to the lower end of the garment. The 3 rows shall be spaced such that the width of the back panel is divided in 4 equal portions. Thread, polyester, size FF, shall be used, 6 to 9 stitches per inch, type 301.

The outer cover of the garment shall be attached to the 7 plies of Kevlar fabric by 1 row of basting, 1/4" from the edge, using thread, polyester, size E, 5 to 8 stitches per inch, type 301 or 401.

The edges of all the panels shall then be covered by binding tape, using nylon tape, 1" wide, type III, MIL-T-5038, natural color. The tape shall be folded in equal parts around the edges and shall

3.5.2 (Continued)

be sewn in place, using 2 rows of stitching, with a needle gauge of 1/4", and a distance of 1/16" from the edge of the tape. Thread, polyester, size FF, shall be used, 6 to 9 stitches per inch, type 301.

3.6 Labeling: Each garment shall have two (2) labels sewn to the inside center of the back panels just below the neckline. The labels shall contain information on identification, size and maintenance.

3.6.1 One label shall contain the following information:

NOTICE: LEAA Prototype Protective Garment ... provided through The Aerospace Corporation, Serial Number __________, Size __________. This prototype protective garment contains seven (7) plies of DuPont Kevlar-29 ballistic material and is provided for evaluation of comfort and wearability only. It is not fully qualified for ballistic penetration, blunt trauma, or environmental considerations. It has been designed and tested to resist the ballistic threat of a .38 caliber special pistol (800 fps), and .22 caliber, 4-1/2" handgun (1000 fps).

3.6.2 The label for care and maintenance requirements should contain the following information:

NOTICE:

1) For Machine Washing use mild setting. Wash at cold temperature using Woolite (or equivalent). DO NOT USE BLEACH OR STARCH.

2) For Hand Washing wash in cold water as described above. DO NOT WRING OR TWIST.

DO NOT DRY CLEAN

Drying

1) Machine dry in tumble dryer using the air cycle (no heat) setting for delicate items. Drying should be conducted for at least one hour. Hang on hanger.

2) To Drip dry remove from washer before last cycle Hang on hanger.

3) Dry thoroughly before wearing.

3.6.3 The indication of size should use the nomenclature defined in 3.7.

3.7 Sizes: Sizes shall conform to the requirements as specified in the following table (1):

TABLE 1

SCHEDULE OF SIZES

Small (34-36)	Medium (38-40)	Large (42-44)	X-Large (46-48)
Short	Short	Short	Short
Regular	Regular	Regular	Regular
Long	Long	Long	Long

All measurements shall be in inches and shall be taken as shown in the attached pattern drawings.

4.0 QUALITY ASSURANCE

4.1 Responsibility for Inspection: Unless otherwise specified in the contract, the contractor is responsible for meeting all inspection requirements as specified herein. The Aerospace Corporation reserves the right to perform any of the inspections set forth in the specifications where such inspections are deemed necessary to assure that the supplies and services conform to prescribed requirements.

4.1.1 Inspection Verification: When certificates of compliance are submitted, The Aerospace Corporation reserves the right to check test any delivered item to verify compliance with the specifications.

4.2 First Article Inspection: The pre-production samples submitted shall be inspected for compliance with design, construction, workmanship, and dimensions. Tolerances on basic dimensions shall be selected from TABLE 2.

TABLE 2

TOLERANCES

BASIC DIMENSION (INCH)	TOLERANCE (INCH)
less than 2"	± 1/16"
2" - 10"	± 1/4"
10" - 30"	± 1/2"
30" - 60"	± 3/4"
more than 60"	± 1"

4.3.1 Inspection of Components and Materials: In accordance with 4.1 above, components and materials shall be inspected and tested in accordance with all the requirements of referenced specifications.

4.3.1.1 Testing of Components: In addition to the quality assurance provisions of the referenced material specifications, testing methods shall be performed in accordance with FED-STD-191 wherever applicable and as specified herein.

4.3.2 Examination of the End Item: Defects found during the inspection of the materials and during examination of the garments shall be classified in accordance with the lists shown in 4.3.2.1 and 4.3.2.2. The sample unit for these examinations shall be one undergarment. The inspection levels and acceptable quality levels (AQL's) for these examinations shall be in accordance with 4.3.2.3.

4.3.2.1 Visual Examination: The garment shall be visually inspected for defects listed below: (REF. MIL-STD-849)

Examine	Defect	Classification Major	Classification Minor
Material defects	Hole, cut, tear, drop stitch, thin area, mends, any.	X	
	Any slub more than twice the thickness of normal yarn.		X

Examine	Defect	Classification Major	Classification Minor
Material defects (continued)	Any accumulation of slubs, clearly visible, causing non-uniform over-all appearance.		X
Color (Class 1)	Not bleached white (cover/shell)	X	
Cleanness	Spots and Stains		X
	Two or more untrimmed ends more than 1" in length inside or outside of garment.		X
Components	Any component missing, or other than specified.	X	
Seams and Stitching	Any seam twisted, puckered or pulled, affecting appearance.		X
	Needle chews	X	
	Tight tension (stitches break when normal strain is applied to seam or stitching).		X
	Loose tension resulting in a loosely secured seam.		X
	Any part of garment badly pleated, caught or twisted in any unrelated row of stitching.	X	
	Any untrimmed seam.		X
Seam type	Wrong seam type	X	
Stitch type	Wrong stitch type	X	
Stitches per inch	Number of stitches per inch exceeding minimum or maximum specified.		X
Open seam (any broken stitch or two or more continuous skipped stitches)	Any open seam, except on hems.	X	
	Any open seam on hems 1/2" or more		X

Examine	Defect	Classification Major	Minor
Stitches skipped or broken (stitches skipped or broken on same row of stitching but not accounting to an open seam)	Skipped or broken stitches more than 1/2 inch	X	
Marking, size and identification	Omitted, incorrect, illegible or misplaced.		X

4.3.2.2 Examination for Measurements: Before measuring the size of the garments, the samples shall be conditioned in normal atmosphere and in a relaxed supported state for a minimum of one hour. Any measurement smaller or greater than specified dimensions including allowed tolerances shall be classified a defect.

4.3.2.3 Inspection Levels and Acceptable Quality Levels (AQL's): The inspection levels and acceptable quality levels expressed in defects per 100 units shall be as follows:

Examine	Inspection Level	AQL Major	AQL Total
4.3.2.1	II	1.5	4.0 (major & minor)
4.3.2.2	S-3	--	10.0 (1 class)

5.0 PREPARATION FOR DELIVERY

5.1 Packaging: Packaging shall be in accordance with MIL-C-43424, except as noted below. Each garment shall be folded in accordance with standard practice to an approximate dimension of 12 x 12 inches. One folded garment shall be inserted into a snug-fitting flat style bag made of 0.00125 inch thick clear polyethylene film. The mouth of the bag, when prepared for closure, shall extend a minimum of 6 inches beyond its contents, measured at the center of the bag. The bag shall be closed by heat sealing, or by triple folding at the mouth and taping the full length of the mouth to the body of the bag with 2 inch minimum width adhesive tape. Prior to or during the bag closing operation, excess air within the bag shall be evacuated.

5.2 Packing: Twenty-five garments of identical size and packaged in accordance with 5.1 shall then be placed in a snug-fitting fiberboard box conforming to Style RSC, Type CF or SF, domestic, Grade 200 of Specification PPP-B-636. The box closure shall be secured with gummed paper tape, not less than 2 inches wide.

5.3 Marking: Shipping containers shall be marked in accordance with FED-Std-123.

5.3.1 Labels: Each shipping container shall have securely attached to the end and side a 4 x 5 inch label indicating sizes and quantity of garments contained.

5.3.2 F.O.B. Point: Prices shall be quoted F.O.B. contractor's plant.

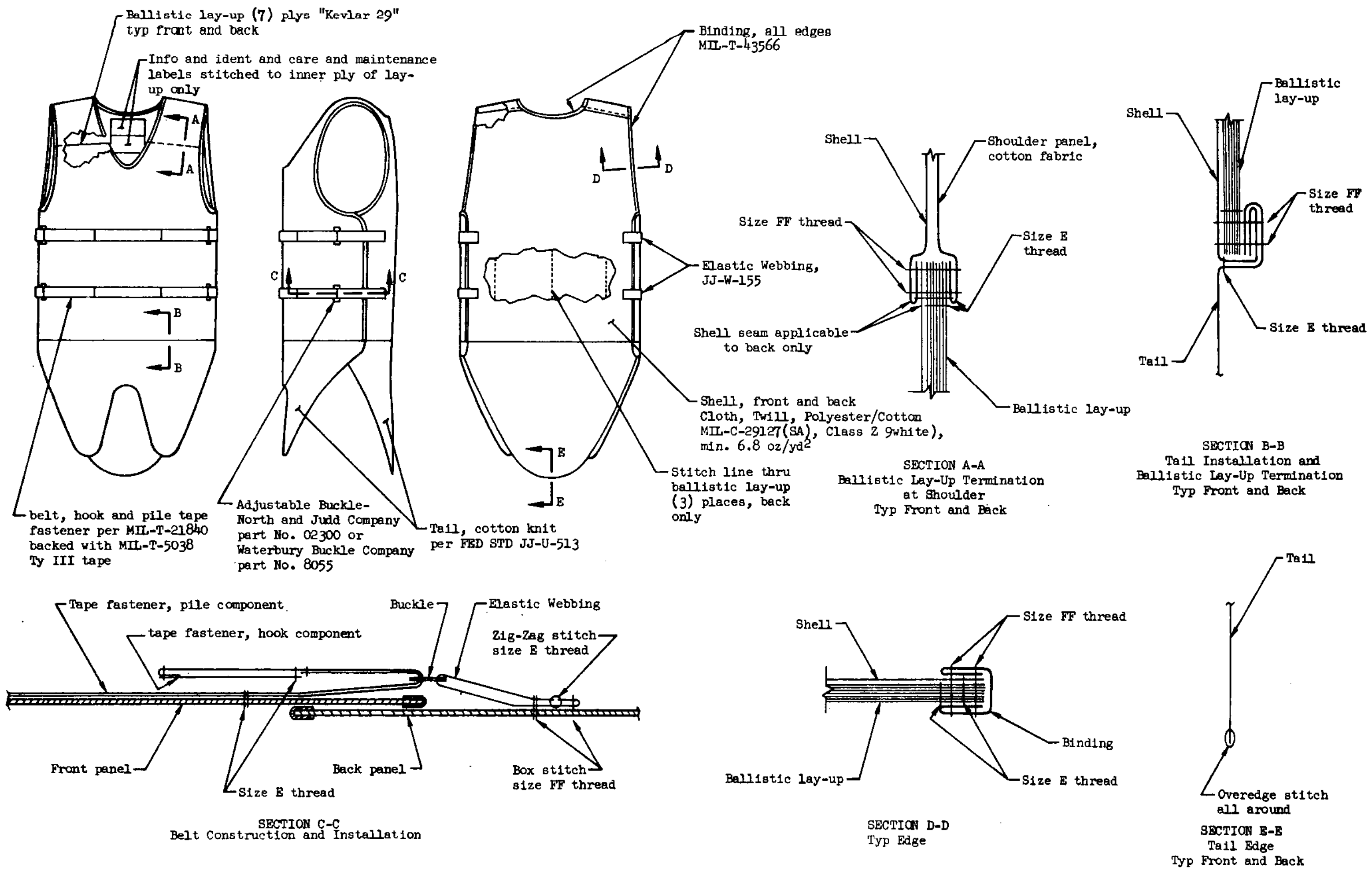


Figure 1. BALLISTIC PROTECTIVE UNDERGARMENT (STYLE 1)

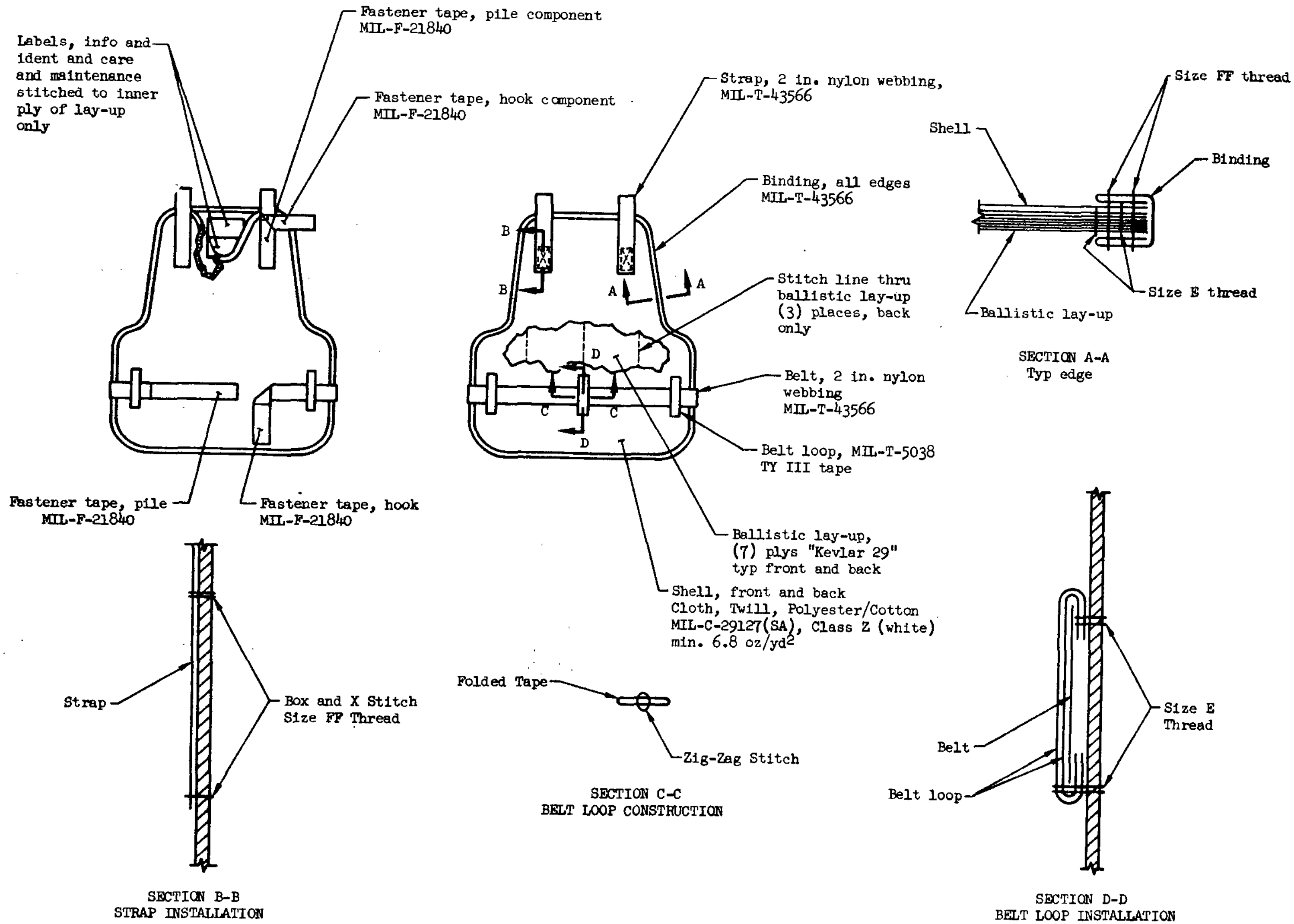


Figure 2. BALLISTIC PROTECTIVE UNDERGARMENT (STYLE 2)

APPENDIX D

SOFT ARMOR TEST MATRIX 1 -- FINAL REPORT

(Lawrence Livermore Laboratory)

TID-4500, UC-38
Engineering and Equipment

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California/94550

UCRL-51677

SOFT ARMOR TEST MATRIX 1 – FINAL REPORT

C. A. Honodel

MS. date: September 19, 1974

SOFT ARMOR TEST MATRIX 1 – FINAL REPORT

Abstract

Contracts 44337-V and 44364-V titled, "Soft Body Armor Test Series" and "Data Analysis of LLL Soft Armor Testing" have been completed. This report describes the experimental activities conducted by LLL in fulfilling these contracts which were issued by the Aerospace Corporation of El Segundo, California.

The test series utilized LLL experimental facilities and diagnostic techniques for the determination and demonstration of the systematic nature of soft body armor corresponding to variations in the armor design and testing parameters. The armor material was composed of DuPont "Kevlar-29"* polyamide strands which were woven into a basketweave, 400 denier cloth.

Background

The Law Enforcement Assistance Administration (LEAA), under its Equipment Systems Improvement Program (ESIP) is providing funding through a prime contractor, The Aerospace Corporation, for the development of lightweight, flexible body armor.

It has been demonstrated that polymeric strands such as DuPont "Kevlar-29," when woven into a basketweave cloth, afford a high resistance to penetration by a standard pistol-fired bullet. It has been proposed that garments fabricated from seven to nine layers of this 400-denier material might be worn by foreign or U.S. Government officials whenever public exposure is arranged. There is a growing expressed interest by law enforcement agencies in similar garments.[1,2]

Preliminary ballistic tests conducted at Edgewood Arsenal[3] indicated that an armor comprising from five to nine layers of PRD-49, 400-denier basket-weave cloth weighing only 0.46 to 0.83 lb/ft^2 can defeat penetration by a .38 special bullet fired from a pistol at full muzzle velocity. While these materials can provide a life-saving function, they normally allow a conical depression to form at the armor/human body interface. This rapidly formed depression can cause injury in the form of severe contusion and/or blunt trauma. This reaction occurs as the material strands are loaded up and the bullet is deformed and decelerated. The impact reaction history was first recorded by flash x-ray techniques developed at LLL[4] and demonstrated in a preliminary

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

one-week feasibility study.[5] Three recent incidents involving shootings of policemen wearing undershirt armor have been studied, the lesions carefully analyzed and the resulting injury reports catalogued for future correlation.

Blunt trauma human/animal correlation experiments are being conducted by the Biomedical Laboratories at Edgewood Arsenal, Maryland. Their testing on goats will establish acceptable injury limits on the characteristic cavity formed by a ballistic impact. A map of human body sensitivity to these craters will guide the designers of the armor.

The LLL testing was performed using gelatin as a human body mock. This technique is biomedically accepted by Edgewood Arsenal and their recipe was carefully followed as described in Appendix A. Gelatin/animal tissue correlation under ballistic impacts by LLL x-ray techniques has been proposed as a logical follow-on to this current test series.

LLL Test Matrix

A series of approximately 26 ballistic testing firings was conducted. They were divided into six groups, each of which was controlled by the variation of one parameter. Table 1 lists these groups and the resulting conical depression factor (C.D.F.).[5] The C.D.F. combines the dimensions of the armor/body interface signature into the form

$$\text{C.D.F.} = \frac{r^2 h^2}{t} \qquad (1)$$

where the value r is the radius (cm) of the depression cone and h is the height (cm) of the cone at the time t (msec) when the velocity of the axial motion has decayed to 5% of the impacting velocity. This factor was plotted as the ordinate in each test group. Equation (1) is purely empirical; it stems from a meeting with the medical and design teams where the factors were combined and their relative importance amplified exponentially.

Group I in Table 1 relates the C.D.F. to the number of plys of Kevlar-29. A plot of the C.D.F.-vs-areal density or thickness would be used for comparison of different armor materials. The ballistic threat is the standard 158-grain lead bullet fired from the .38-cal. pistol. The control velocity is 800 ft/sec which is near the muzzle velocity. The number of plys chosen represent the minimum (3) which will defeat penetration and the maximum (15) which is reasonably flexible and affords a minimum C.D.F.

Group II relates the C.D.F. to the standoff distance between the armor and the supporting backup gel. The distances range from zero to 1.5 in. Again, the ballistic threat was the .38 special, 158-grain lead bullet at 800 ft/sec.

Group III relates the C.D.F. to the impacting bullet velocity. This is important as the range increases and the impact velocity is reduced. The range chosen spans from super-velocity (977 ft/sec) to 565 ft/sec. The threat is the .38 special lead bullet.

Group IV relates the C.D.F. to a different ballistic threat. The .22 calibre long rifle bullet is fired at various ply-count

Table 1. Test matrix grouping.

Group I. The effect of the number of plys of Kevlar-29.

Shot No. 384-UG-	Cal.	Velocity (ft/sec)	Plys	C.D.F.
-1.	.38	761	3	463
-3.	.38	841	5	336
-5.	.38	827	7	261
-6.	.38	810	9	207
-7.	.38	854	15	159

Group II. The effect of standoff.

Shot No. 384-UG-	Cal.	Velocity (ft/sec)	Stand-off (in.)	Plys	C.D.F.
-8	.38	860	0.5	7	337
-9	.38	787	1.0	7	315
-10	.38	846	1.5	7	277

Group III. The effect of bullet velocity.

Shot No. 384-UG-	Cal.	Velocity (ft/sec)	Plys	C.D.F.
-14	.38	565	7	159
-16	.38	670	7	148
-15	.38	863	7	262
-11	.38	977	7	217

Group IV. The effect of ply count on penetration of a .22 cal. projectile.

Shot No. 384-TG-	Cal.	Velocity (ft/sec)	Plys	C.D.F.
-1	.22	1040	7	59.6
-2	.22	1033	9	43.3
-3	.22	1092	15	35.3

Group V. The effect of ply count on jacketed 9-mm projectile.

Shot No. 384-UG-	Cal.	Velocity (ft/sec)	Plys	C.D.F.
-17	9 mm	1150	18	150.6
-19	9 mm	1150	23	177.9

(Table 1 continued)

Group VI. The effect of bullet caliber at constant impact energy.

Shot No. 384-	Cal.	Velocity (ft/sec)	Plys	E_j	C.D.F.	Proj. weight (grains)
-TG-4	.22	1653	16	340	Penetration	38.4
-MG-2	.30	913	16	340	131	146
-UG-23	.38	765	16	340	178	206

targets. The bullet is the lead .22LR impacting at a muzzle velocity of approximately 1000 ft/sec. The ply count ranges from 7 to 15.

Group V relates the C. D. F. to a third threat, that afforded by the 9 mm copper-jacketed bullet. It weighs 115 grains and has a muzzle velocity near 1150 ft/sec. The results in groups I, IV, and V are roughly comparable.

Group VI is a comparative ballistic study where the bullet energy is held constant (by controlling the velocity) while the bullet cross-sectional area is varied. This preliminary series is aimed at the prediction of the C. D. F. with respect to various ballistic threats. The impacting bullet energy for the three shots is maintained at approximately 340 J. The bullet cross-sectional area varies from 21.5 mm^2 for the .22LR to 64.2 mm^2 for the .38 special.

Experimental Set-Up

Figure 1 shows the laboratory layout. This facility is located in Bldg. 341. The test vault is temperature-controlled, light-controlled, and remotely operated. Three test barrels were used for this series, a 10 in. XP-100 Remington, a 26 in. .350 Remington and 24 in. smoothbore .30-06. These barrels are cart-mounted and electrically actuated. See Fig. 2. The bullets used (see Fig. 3) were:

1. Hornady Type .38 calibre, 0.358 in. diam, round nose, 158 grain.
2. Winchester type B38S3P, 200 lead (200 grain).
3. Winchester type BW9LP, 9 mm Luger, FMC, 115 grain.
4. Cast lead alloy from Lyman Mold No. 225107, .22 calibre, 38 grain.
5. Cast lead alloy from Lyman No. 300136, .30 calibre, 146 grain.

The cases used were .350 Remington Magnum for the .38 and 9 mm bullets, 30.06 Remington for the .30 cal., and the .221 Remington Fireball for the .28 bullets. The loadings were reduced and the powders used were IMR 4227 (9 mm), IMR 4350 (.38, 158 gr.), and IMR 3031 (.30 cal., 146 gr. and .22 LR). The .350 RM barrel was cut down to 13 in. after the test series in an attempt to stabilize the low velocities. A typical velocity/load curve (Fig. 4) indicates less than 1% spread in the velocity for a given loading series.

The velocity traps afford redundant readings by virtue of the third foil grid

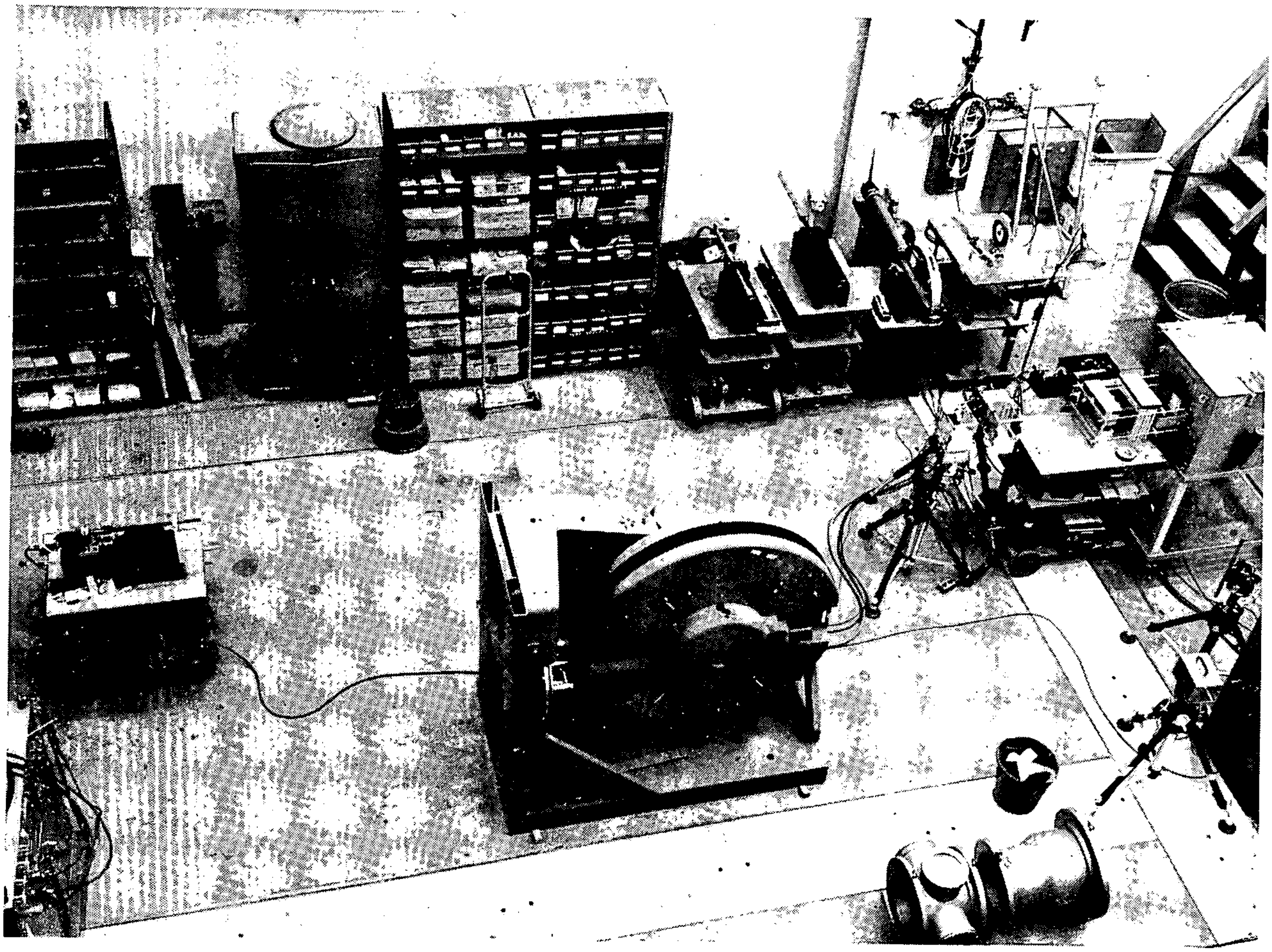


Fig. 1. Overhead view of the Vault 2 laboratory. The gun cart is seen to the left and the target cart to the far right. The high-speed camera is in the center foreground.

switch or one double-length 498 mm section as shown in Fig. 5. The rear third foil provides the trigger for the flashlamp which provides the photographic illumination. The flashlamp is the FT623 (G.E.) and is driven by a 12 kJ capacitor bank. As used for this test series, the bank is adjusted to operate at 3.6 kV and 960 μF (6350 J). The bank is spark-gap triggered on, and triggered off through an Ignitron tube into a low inductance load. The turn-off time of the lamp is as quick as the turn-on time except for the tail pulse which is below the film exposure threshold within the shutter-gate time.

The high-speed camera used for most shots was the Beckman & Whitley Model 192. This is a continuous access, 80-frame, 35 mm film camera with sub-microsecond interframe capabilities. For this shot series the rotating, turbine-driven mirror was slowed to give an interframe time of 20 μs. This appears to be near the optimum record length since the velocity, on axis, for any of the tested targets has degraded below 5% of impact before this time.

The streak camera used for Shot 384-UG-25 was the LLL Model 100. This is a continuous-access 35-mm-film camera

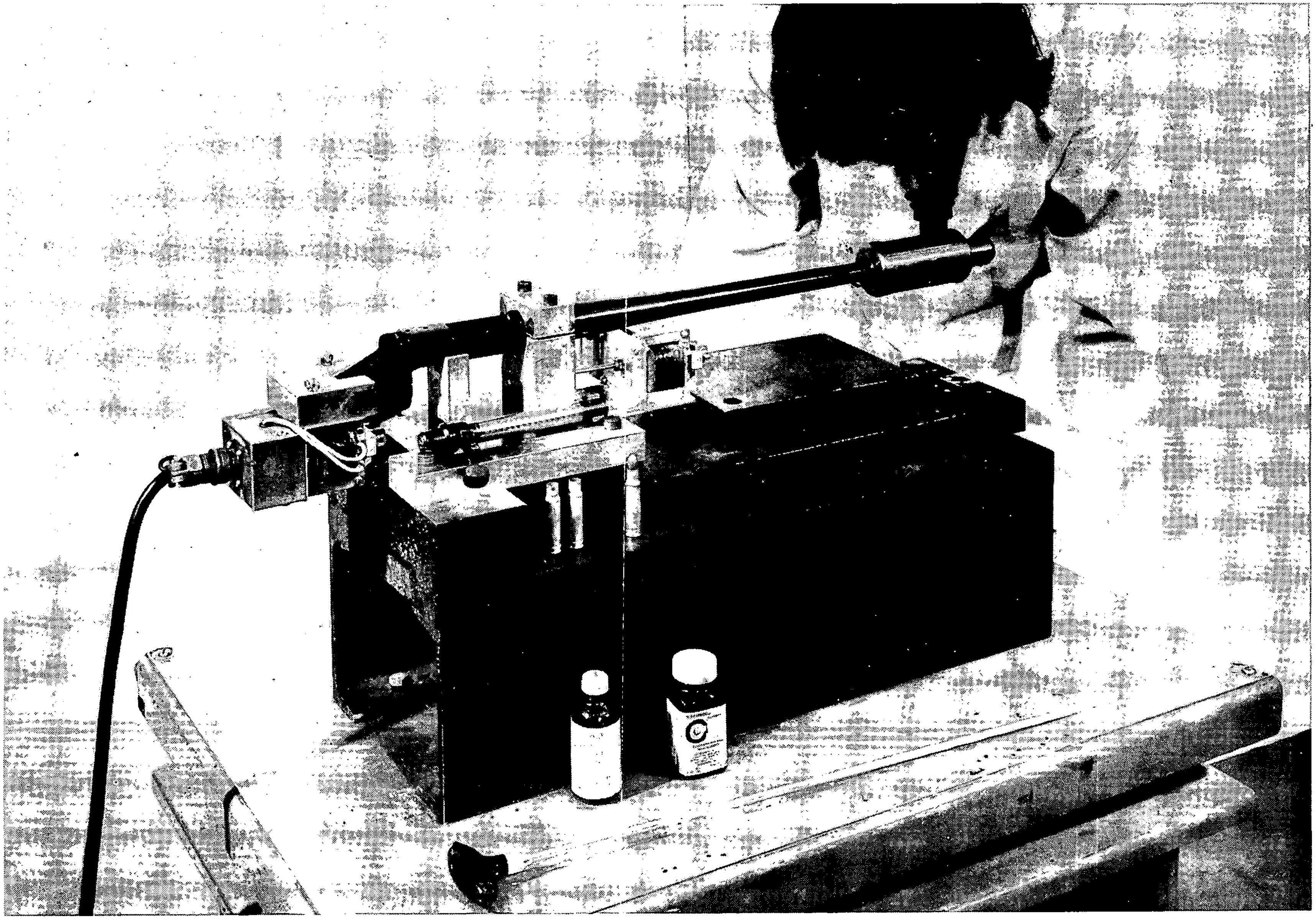


Fig. 2. Optical alignment of the .350 Remington barrel to the soft armor target.

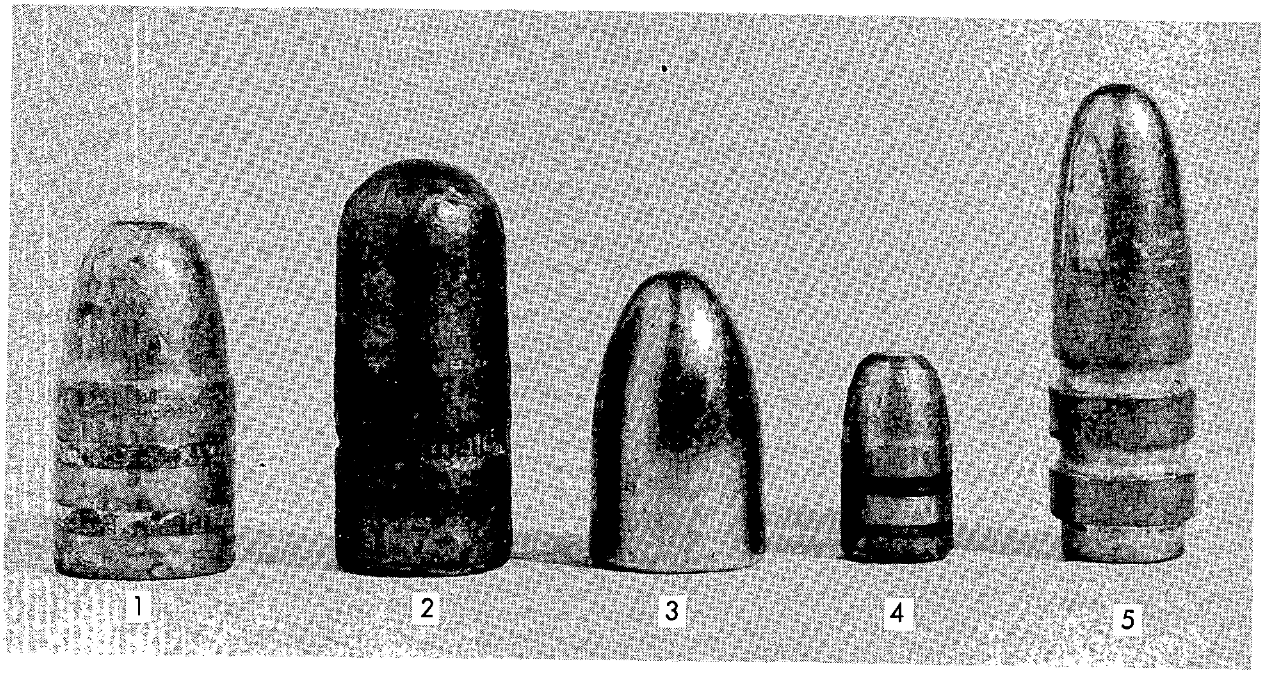


Fig. 3. The bullets used for this test series: (1) Hornady type .38 caliber, 0.358 in. diam round nose, 158 grain. (2) Winchester type B38S3P, 200 lead (200 grain). (3) Winchester type BW9L9, 9 mm Luger, FMC, 115 grain. (4) Cast lead alloy, Lyman No. 225107, .22 caliber, 38 grain. (5) Cast lead alloy, Lyman No. 300136, .30 caliber, 146 grain.

with an eight-sided turbine-driven mirror. The rotor speed was reduced to 100 rps for this shot in order to create a reasonable slope for the axial velocity calculation. It yields a continuous velocity profile and can be used to advantage when subtle changes in surface motion are anticipated.

The velocity traps, the target mounting frame, the gelatin block and backup cellotex sheets are all clamped to a ballistic catcher box and are supported on a mobile cart as shown in Fig. 6. The flashlamp is tripod supported and the light masking is taped to the target assembly. The optical path is folded by a first-surface turning mirror which also aids in the alignment process.

Following a prepared preshot form (Fig. 7), the firing procedure is to position the refrigerated gel block and mount the target and its frame into optical alignment. The gun barrel is optically aligned and the flashlamp is positioned and masked. Velocity trap foil switches are attached and tested. The camera is loaded with film and final optical alignment is checked.

The temperature of the gel is monitored and the shot is scheduled to coincide with a temperature rise to 10° ± 2°C. Finally, the cartridge is loaded into the breech and when safety is assured, the bolt is positioned and put in the firing condition. The room lights are turned off for camera operation as the firing technician leaves the area and the door interlocks are made up on closing.

The firing console is located outside the firing vault (Fig. 8) and contains the required operational safety interlocks, diagnostics and systems monitor chassis.

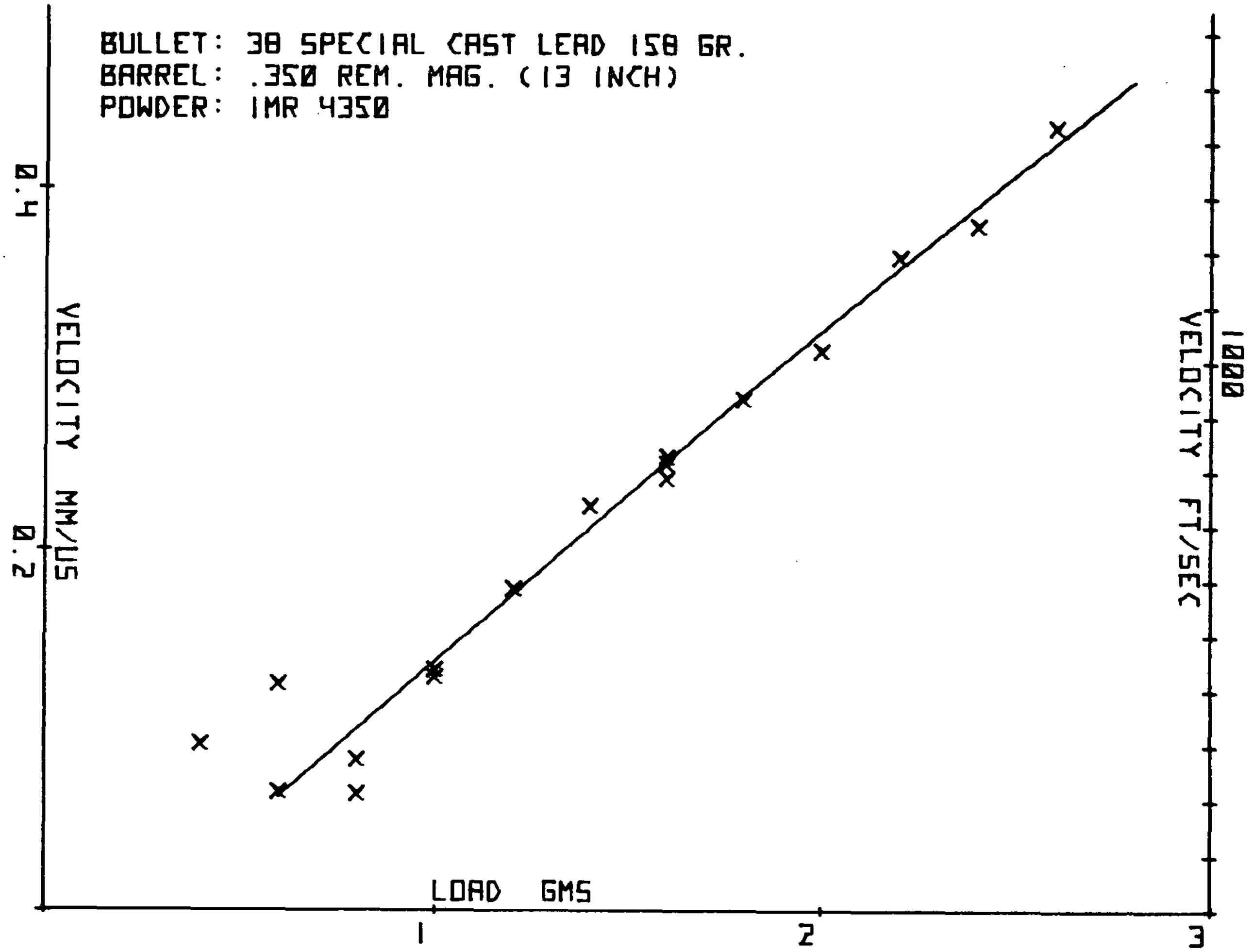


Fig. 4. Computer-generated load vs muzzle velocity plot of data obtained using a .38 cast lead bullet in a 13-in. .350 Remington barrel with IMR4350 powder.

When the safety interlocks are secured and the flashlamp bank is charged, the camera is run up to speed and the system is fired. After firing and when safety is assured the vault is entered, the gun system secured and the film is unloaded from the camera. The time interval counters are read and recorded on the preshot form and the lamp monitor scope is reviewed. If the shot is deemed successful, the film is processed and prepared for data reduction. The form titled "Soft Armor Test Matrix 1 – Raw Film Data" (Fig. 9) was prepared for this series and each shot film is accompanied by this sheet.

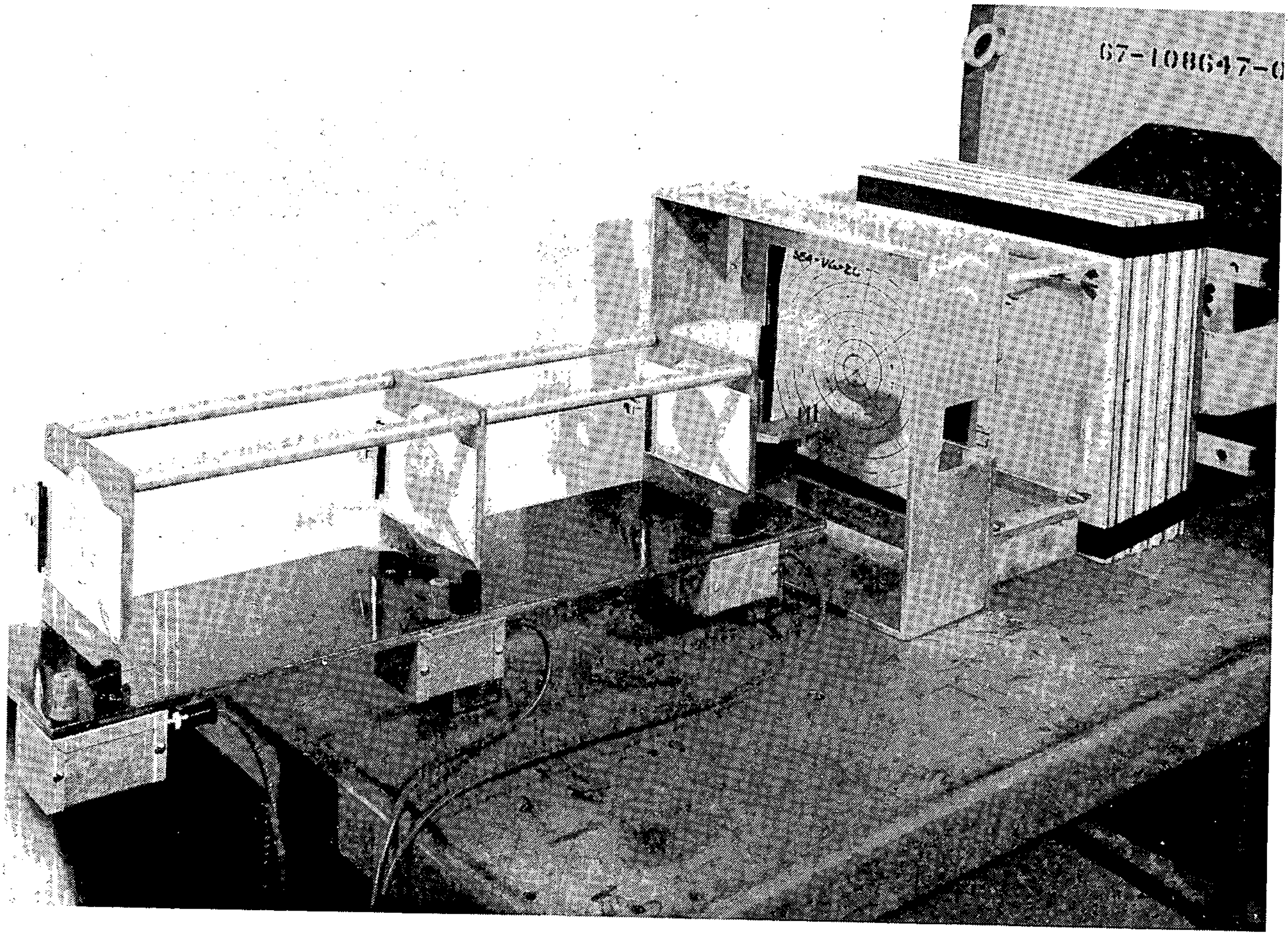


Fig. 5. Foil switched, 2-stage velocity trap.

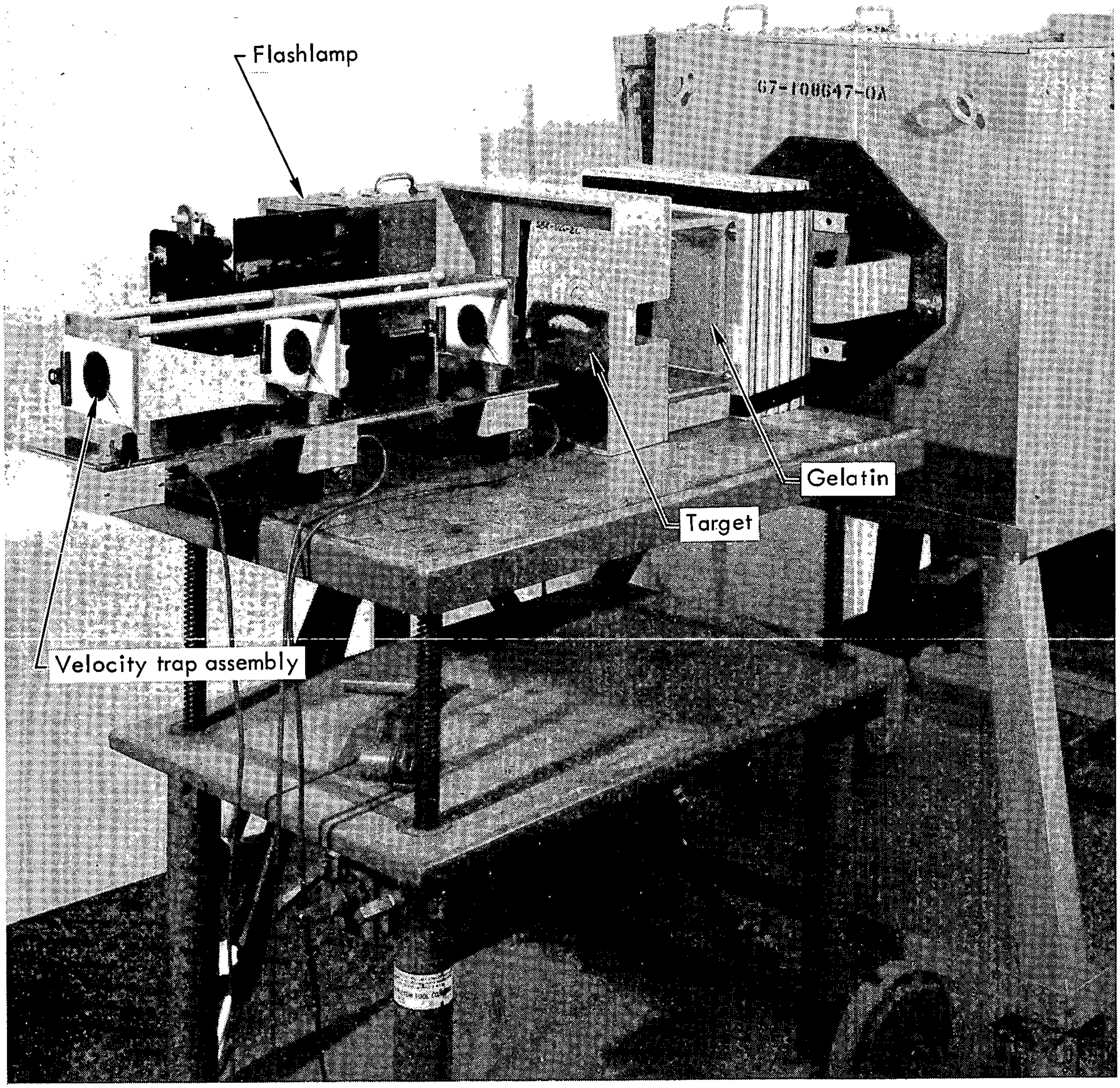


Fig. 6. Target cart with velocity trap attached.

OVERHEAD LIGHT
(FRONT & REAR)

REQUESTOR CH

SHOT NO. 384-UG-
ACCT. NO. 6877-05

THIS SHOT DOES ☐ / DOES NOT ☑ CONTAIN TOXIC MAT'L

DATE FIRED 6-27-74

BAY NO. ____ RANGE DIST. 20'

PROGRAM SELECTOR NO. ____

BARREL .350 REM. MAG.

VELOCITY TRAP:

BULLET VELOCITY:

TYPE GRID SWITCH

REQUESTED 825'/sec = .251 mm/μs

TRAP LENGTH 249, 249, 498 mm

MEASURED 663'/sec = .202 mm/μs

DIST. FROM TARGET 8 1/4" = 210 mm

CARTRIDGE: TYPE .350 REM. PRIMER AS PRIMED POWDER IMR 4350 AMOUNT (1.70) 1.30

BULLET: TYPE .38 CAL. 158 gr SHAPE RD NOSE HARDNESS Pb MARKING ____

DIAGNOSTICS: 20 μs INTERFRAME

	MODEL	ROTOR SPEED	FILM TYPE	STOPS	OBJ. LENS	SLIT	FIL.	EPUT
CAMERA 1	192	214.3	TRI-X	.10"	24"	-	NONE	
CAMERA 2								

ILLUMINATION: 1 ea. FT623, 3.6 KV, 960 μfd. = 6350 j

FILM DEVELOPMENT: DEV. ACUFINE TEMP. 72°F TIME 6 min DEV, 5 min FIX

FXR: SYSTEM ____ ARRANGEMENT ____

VOLTAGE ____ FILM PACK ____

FXR FILM DEVELOPMENT: DEV. ____ TEMP. ____ TIME ____

COUNTERS:

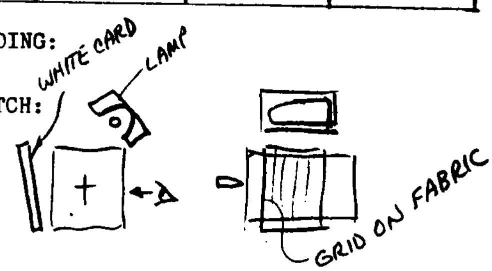
PURPOSE	TYPE	TRIGGER SOURCE START	TRIGGER SOURCE STOP	PULSE POLARITY	~~ATTEN.~~ TRIG.	T.I.M. [redacted]	VELOCITY mm/μs [redacted]	ft/sec. [redacted]
PROJ V		SW #1	SW #2	+ +	+10V	1227.57	.203	666
|		" 2	" 3	|	|	1238.53	.201	660
|		" 1	" 3	|	|	2466.09	.202	663

TARGET:

LAYER	MATERIAL	SIZE
FACING	KEVLAR-29	7 PLY x 9" x 9"
INTER.	400 DENIER	x x
BACKING		x x

BONDING:

SKETCH:



PURPOSE: OVERHEAD LIGHTING TO SHOW EXCURSION OF GEL INTERFACE, REPEAT OF UG-5

TIMING CALC:

LAMP TRIG. TIME = d TRIG. TO IMPACT (D) / PROJ. VEL. (V) - 200 μs = 635 μs

LAMP DURATION = 1450 μs

PENETRATION:

WT. OF FIRED PROJ. ____

ABOVE V_{50} ☐ ____

BELOW V_{50} ☐ ____

RESULTS:

DELAYS: 1 = 0 μsec 2 = 635 μsec TRIG. DELAY
3 = 1000 μsec 4 = 450 μsec LAMP DURATION

- GEL = 10°C

Fig. 7. Firing request data form.

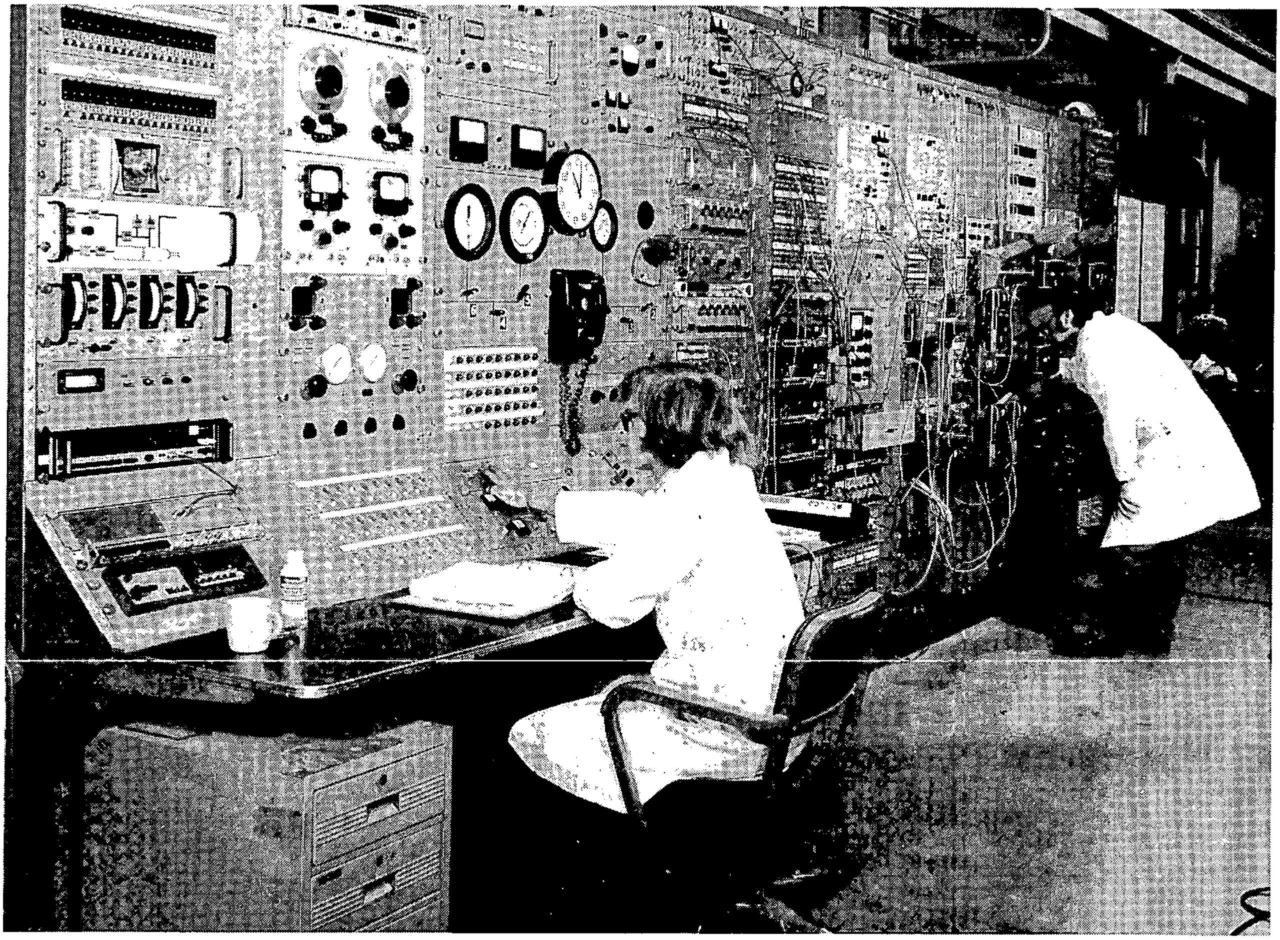


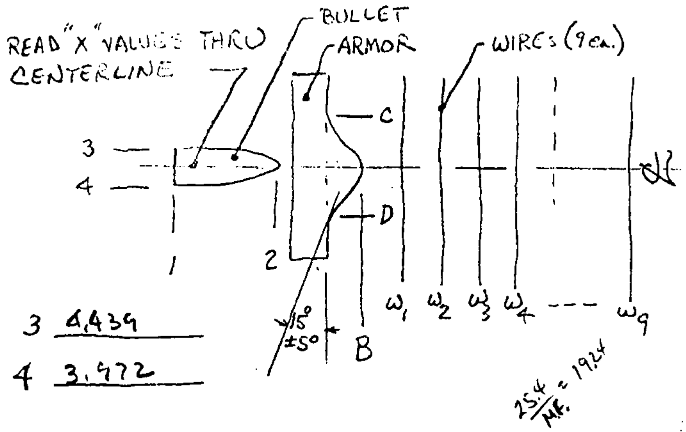
Fig. 8. Vault 2 firing console.

SOFT ARMOR TEST MATRIX 1 - RAW FILM DATA

GROUP V 9mm

SHOT NO. 384-06-17 NO. OF PLYS 18 ARMOR MATERIAL KEVLAR-29 400-2

BULLET VELOCITY 345 m/s = 1132'/sec BULLET TYPE & WT WIN. BW9LP, 115gr. FMC



READING INTERVALS

STATIONS	FRAME NOS.
1,2	
B, FID	2 to 10, 12, 18, 22, 32, 42, 52, 62
C,D	4, 6, 8, 10, 12, 18, 22, 32, 42, 52, 62
W_1 to W_9	0, 18, 52
* PRINTS	-1, 6, 12, 62
MAG. FACTOR*	1.320

$$\text{MAG. FACTOR} = \frac{\frac{1}{2}[(\omega_7-\omega_5)+(\omega_6-\omega_1)]}{1.964 \text{ in.}}$$

t	FRAME	1	2	B	C	D	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	TIME FID	Bo-B (mm)
40	2			3.250												1.643	3.07
60	3		C-P (mm)	3.390												1.611	4.40
80	4		26.82	3.553	4.907	3.513										1.627	9.05
100	5			3.668												1.619	11.58
120	6		36.94	3.763	5.362	3.442										1.615	13.53
140	7			3.827												1.595	15.15
160	8		43.77	3.927	5.706	3.431										1.615	16.70
180	9			3.992												1.601	18.23
200	10		47.09	4.087	4.899	2.452										1.642	19.27
240	12		50.02	4.210	4.899	5.300										1.630	21.88
360	18		55.16	4.407	6.344	3.477	3.620	4.251	4.749	5.234	5.729	6.219	6.753	7.268	8.311	1.574	26.77
440	22		56.14	4.587	5.757	2.839										1.663	28.57
640	32		62.22	4.781	5.979	2.745										1.685	31.86
840	42		66.60	4.909	5.631	2.169										1.682	34.75
1040	52		71.34	4.975	5.924	2.215	3.767	4.404	5.054	5.483	5.929	6.393	6.882	7.373	8.396	1.651	36.26
1240	62		76.69	5.008	5.967	1.981											
0	0			3.058			3.568	4.078	4.595	5.120	5.632	6.156	6.685	7.200	8.242	1.610	
				B0			.510	.517		ave .510						1.659	

Fig. 9. Raw film data and preliminary calculation form.

Data Reduction

The projectile impact velocity is established by averaging the velocities of the two trap intervals (see Fig. 5). This should be identical to the average velocity as timed from the beginning of trap 1 to the end of trap 2. This is the recorded velocity unless one of the foils or a time interval counter fails to function. In that case, the recorded velocity is the average value through the one operational trap. This shot series contains only two shots wherein the velocity was established by a single trap. The readings are always compared with the load/velocity curves and no ambiguous values are accepted in the data reduction.

Electronic circuits were designed to produce optimized trigger pulses from the trap foil switches to the time interval counters. The counters used had 10 nsec resolution. The trap lengths were corrected to 249 mm each and the calculation of a typical velocity near 350 m/sec or 1150 ft/sec will yield an accuracy of one part in 7×10^4. The velocity agreement between traps is doubly dependent on the common center foil position and is typically within 0.5%.

The developed high-speed-camera films were placed in a Vanguard film analyzer (Fig. 10) and each frame was indexed, measured with x-y cross hairs and recorded on the Raw Film Data Sheet. Measurements were taken along the bullet axis for the determination of the cone height position and timing. The cone base diameter was determined by constructing a tangent intercept at 15° from the target normal surface.

The true size was established for each film by calculating a magnification factor from the projected image size on the film reader and normalizing all the measurements to this value. The wires positioned in the gelatin are 1 in. behind the bullet's axial image plane and are spaced at intervals of 10 mm and 20 mm after the seventh wire. An equation was derived which quickly produces the frame magnification:

Magnification factor

$$= \frac{1/2\ [(W_9 - W_5) + (W_6 - W_1)]}{1.969} \qquad (2)$$

where W is wire position and the increments $W_9 - W_1$ are the extreme distances readily measured on the film (true value is 1.969 in. (50 mm)). Further, a constant for the metric conversion was applied and the true distances were calculated and used in the graphs.

Three values were extracted from each measured frame, the height of the conic depression, the diameter at the base of the cone and the time of occurrence. The cone height is plotted with respect to time and the velocity slope corresponding to 5% of the impact velocity is overlayed and the tangent point is marked. This establishes values of h and t in the C.D.F. Eq. (1).

The r value is measured from the diameter-vs-time curve at the time established for the cone height h. The complete list of these values and the resulting C. D. F. values appear in Table 2.

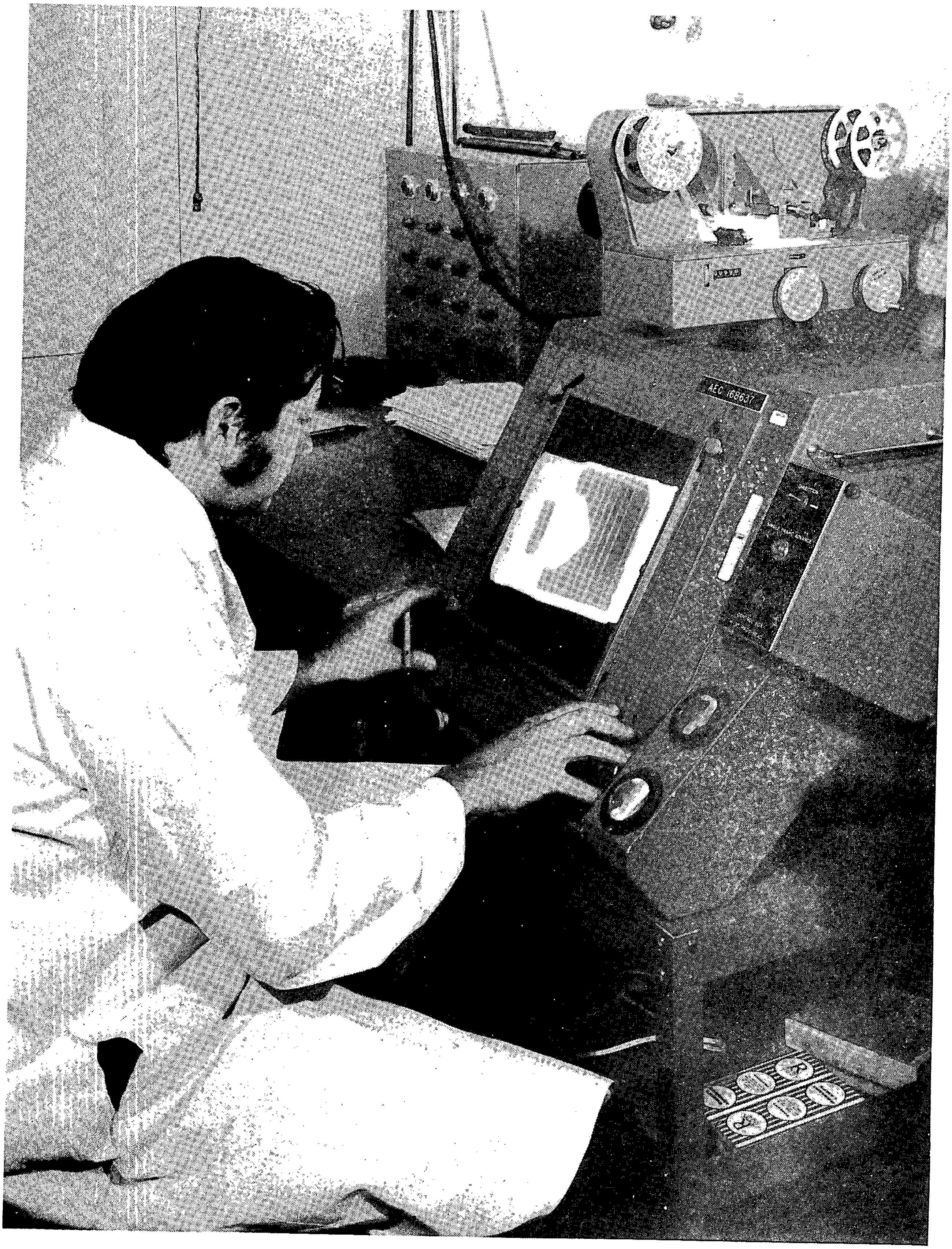


Fig. 10. Shot film readings taken on the Vanguard motion analyzer.

Table 2. Tabulated values for the determinations of the C.D.F. ±10%.

Test group	Shot No.	t (msec.)	r (cm)	h (cm)	C.D.F.
I	384-UG-1	0.80	3.7	5.2	463
	-3	0.80	3.45	4.75	336
	-5	0.94	3.3	4.75	261
	-6	0.78	3.3	3.85	207
	-7	0.60	3.1	3.15	159
II	384-UG-8	1.16	3.5	5.65	337
	-9	1.34	3.7	5.55	315
	-10	1.44	3.7	5.4	277
III	384-UG-11	0.66	2.85	4.2	217
	-14	1.02	3.4	3.75	159
	-15	0.76	3.4	4.15	262
	-16	0.84	2.9	3.85	148
IV	384-TG-1	0.49	2.35	2.3	60
	-2	0.54	2.15	2.25	43
	-3	0.46	2.45	1.65	36
V	384-UG-17	0.52	2.95	3.0	151
	-19	0.78	3.1	3.8	178
VI	384-UG-23	0.94	3.45	3.75	178
	-MG-2	0.68	2.95	3.2	131
	-TG-4	Full penetration			

Experimental Results

The aim of each test group was to demonstrate the C.D.F. dependence on a controllable variable. Each group will be discussed here.

GROUP I

The purpose of Group I was to illustrate the dependence of the C.D.F. on ply count or target thickness. Figure 11 is a family of curves comparing cone height vs time for various thicknesses or ply count targets. As expected, the thinner targets allowed a deeper depression into the gel block. It was surprising to find that the time required to degrade to 5% was quite similar for the whole group, ranging from 0.60 to 0.94 ms.

The base diameter corresponding to 5% of the initial bullet velocity was extracted from the family of curves shown in Fig. 12. The circles correspond to those times. These data allow the calculation of the C.D.F. and the plot in Fig. 13 (Test

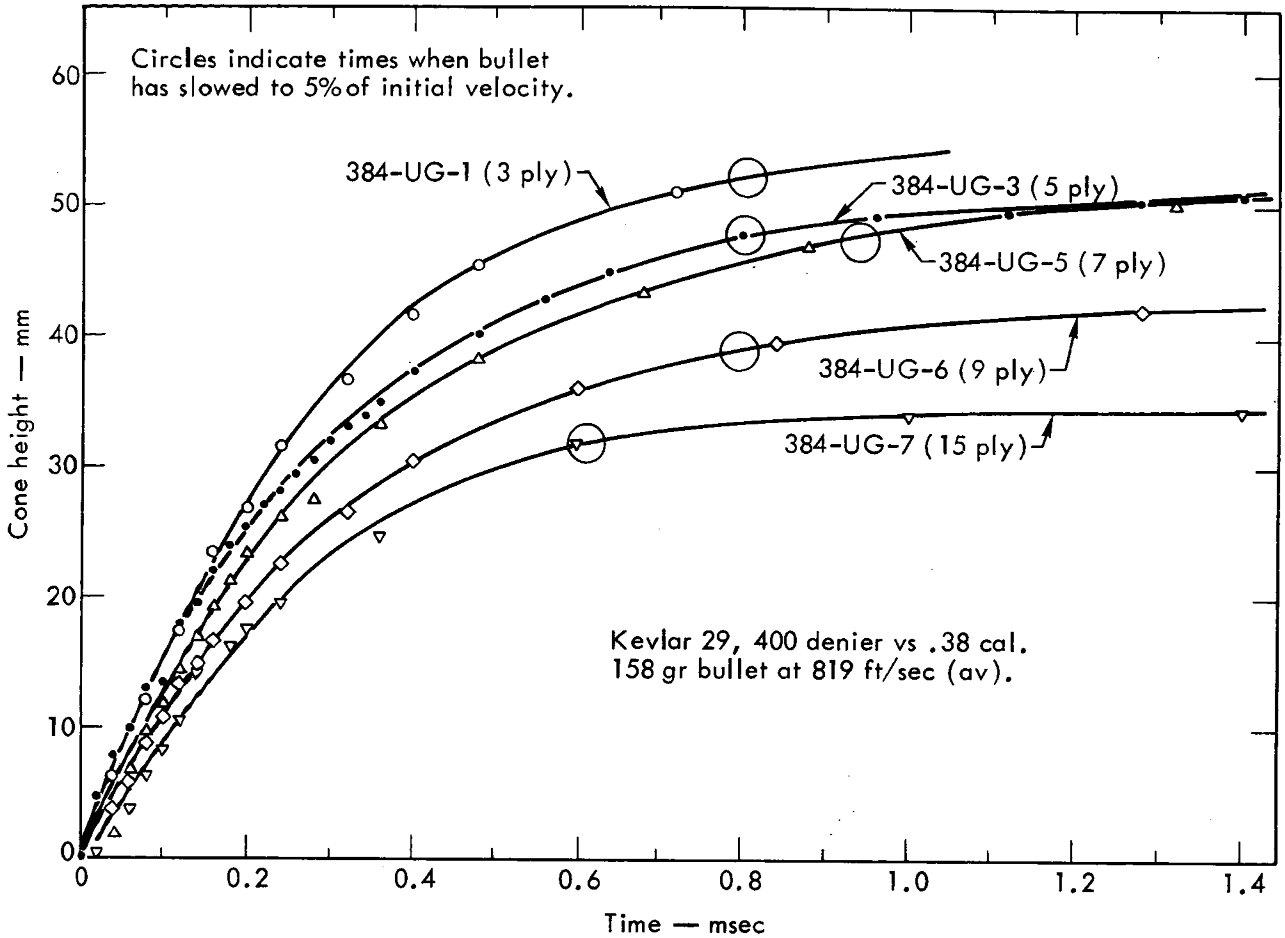


Fig. 11. Effect of armor ply count on cone height. See Table 2, Group I.

Group I) which compares the ply count with the C.D.F.

GROUP II

Test Group II was an attempt to demonstrate the effect of armor standoff. It was presumed that a gap between the armor and the wearer's body might afford some additional protection. When the C.D.F. was calculated using the curve families shown in Figs. 14 and 15 and plotted in Fig. 16, a systematic trend was indicated. It was discovered, however, that a lower C.D.F. was developed at zero standoff. It appears that some shear forces are coupled at the armor/gelatin interface, and inertia from the gelatin aids in reducing the depression height. This effect may affect any testing program where the contact with the backing animal or gel is not controlled. The shape of the Fig. 16 curve may actually contain a much sharper inflection slightly above zero standoff. Resolution of this phenomenon would require several shots in the range of zero to approximately 1 in. standoff. The zero standoff as controlled in the laboratory is probably not realistic for armor applications. The effect of some intervening material such as a cotton undershirt has not been studied.

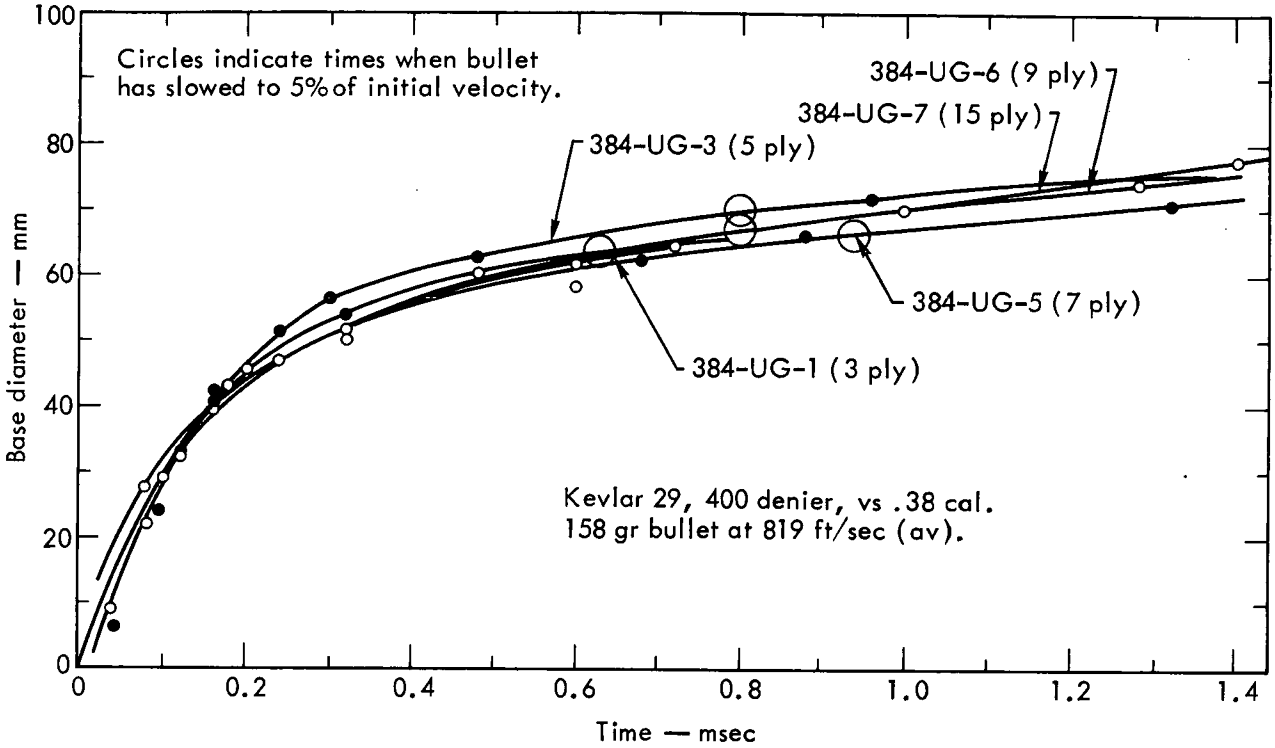


Fig. 12. Effect of armor ply count on cone base diameter. See Table 2, Group I.

Shot 384-UG-10 with its 1.5 in. standoff afforded the measurement of the cone height as formed in air instead of the gel backing. When the h vs t is plotted in Fig. 17, the resultant bullet tip velocity and its apparent kinetic energy can be calculated. The x-ray series performed earlier showed that the bullet is squashed but maintains its integrity during this early impact reaction. It seems clear that more attenuation in the velocity afforded by the armor suspended in air will result in a lower C.D.F. Two ways to accomplish this come to mind: (1) increase the mechanical stiffness of the armor and (2) increase the areal density of the armor. Neither of these options is desirable. Some thin mosaic of stiff, light material backed by the Kevlar might provide some beneficial attenuation while staying reasonably light and flexible.

GROUP III

Test Group III studied the effect of various projectile velocities. A standard seven-ply target was used with the 158-grain lead bullet in .38 calibre. As expected, the family of curves comparing cone height vs time after impact were logically spaced and the 5% velocity intercepts were very consistent (Fig. 18). On the other hand, the curve family of base diameter vs time seemed mixed and unrelated (Fig. 19). A comparison of all these measurements indicates the inaccuracy of the assumption that the depression cone is axisymmetric. Aerospace shot recoveries using clay back-up for depression measurements showed a distinct rectangular-based pyramid shape in the clay depressions.[6] Furthermore, the high-speed framing

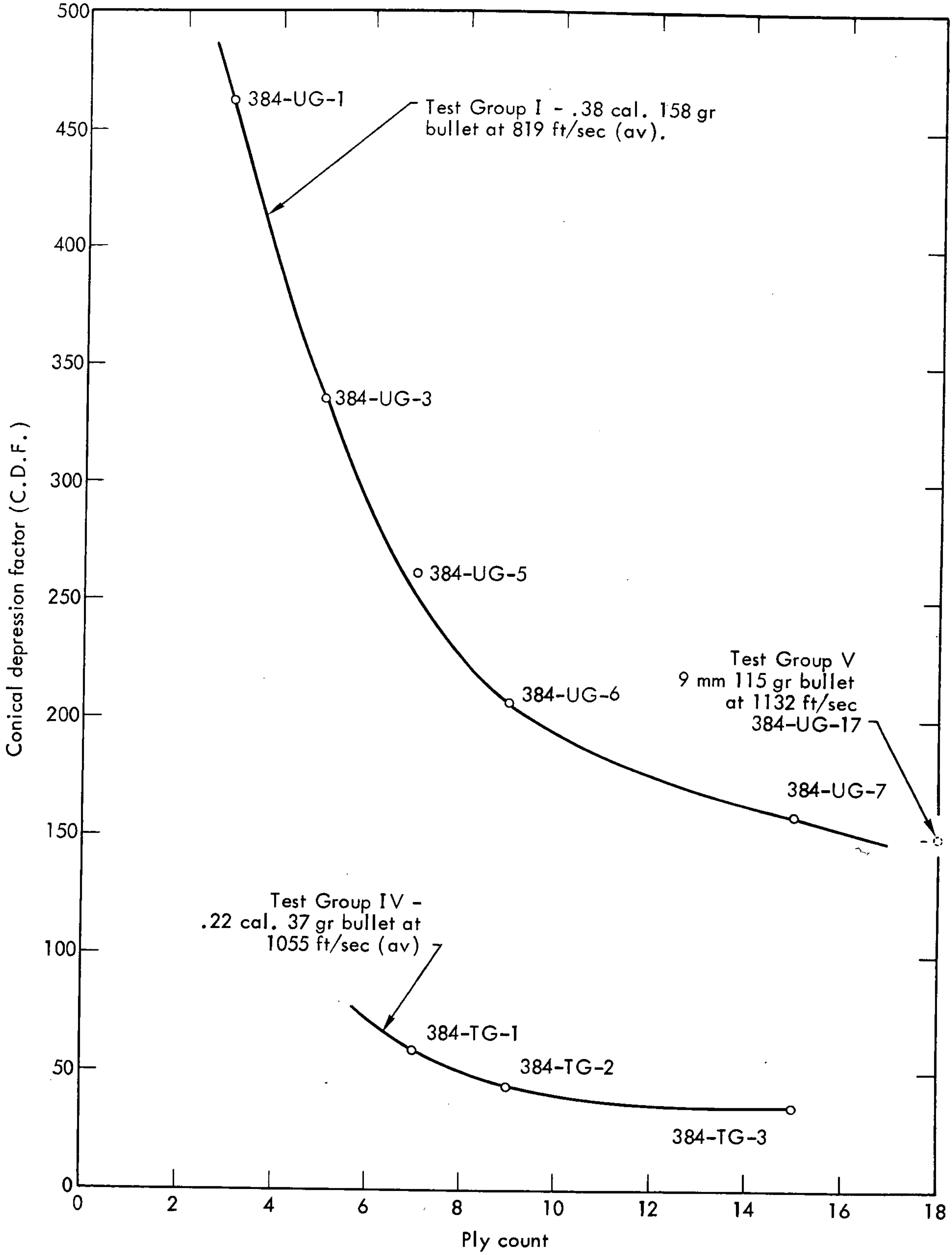


Fig. 13. Effect of Kevlar 29, 400 denier, armor ply count on the conical depression factor (C.D.F.). See Table 2, Groups I, IV, and V.

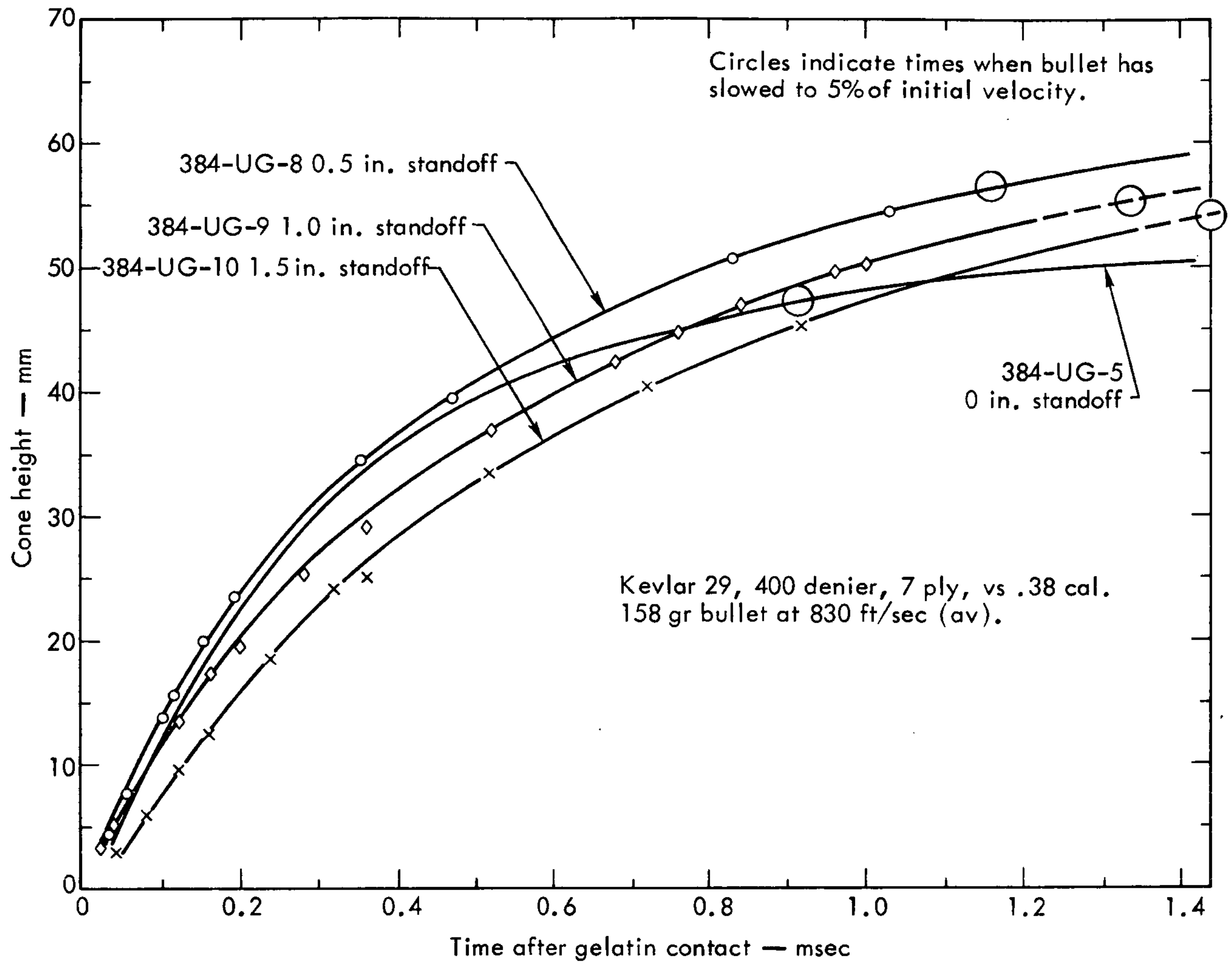


Fig. 14. Effect of armor standoff on cone height. See Table 2, Group II.

camera record (Fig. 20) showing the bullet impacting the Kelvar target illustrates the nonuniform strain that confused the measured values of the base diameter.

Future shots could be performed by selecting a weave directional orientation other than the 0° and 90° used in this series. The intention would be to force the depression to approximate a right circular cone and allow a consistent measurement of the cone base diameter. This should reduce the scatter in the value of r used in Eq. (1) and listed in Table 2. The scatter in these data plotted in Fig. 21 can be attributed to the erratic values of r as used in the C.D.F. calculations.

The dependence of the C.D.F. on impact velocity is important when the firing range is considered. The ballistic threat and C.D.F. are normally reduced by decreasing the velocity of impact, e.g., by increased firing range. A smooth curve such as suggested on Fig. 21 could be established for each candidate armor so that the effect of firing range can be evaluated and used for the selection of armor.

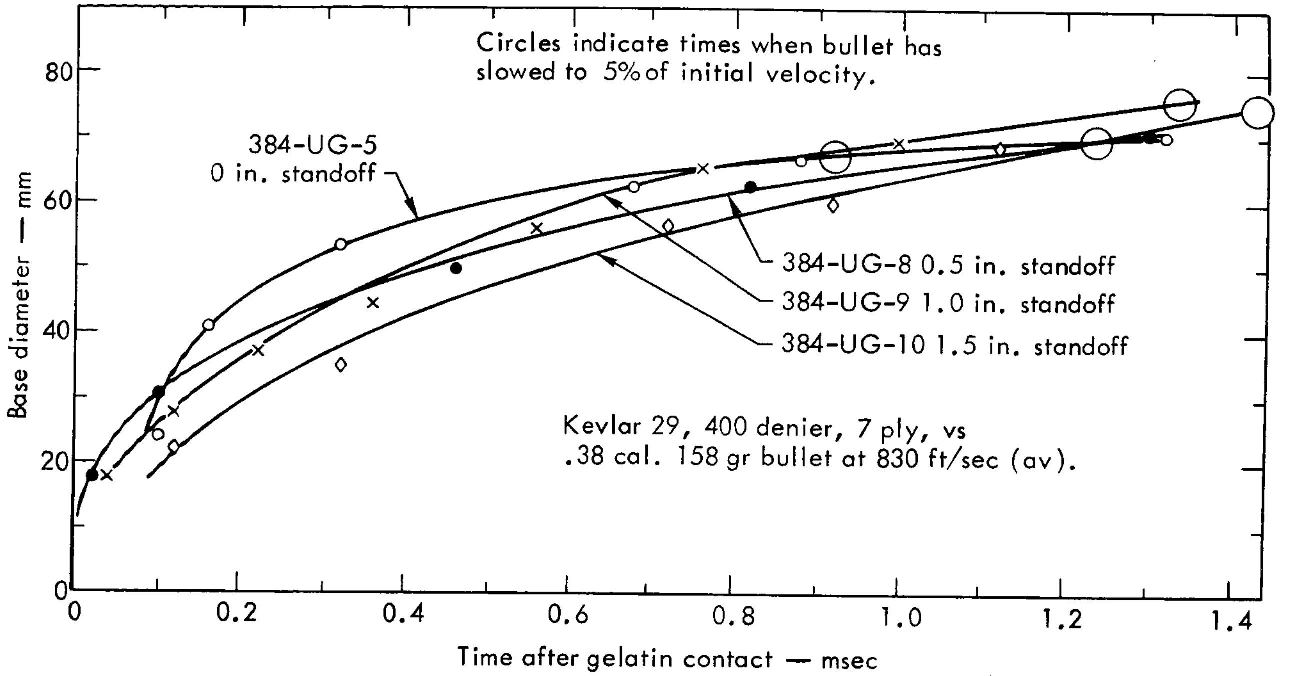


Fig. 15. Effect of armor standoff on cone base diameter. See Table 2, Group II.

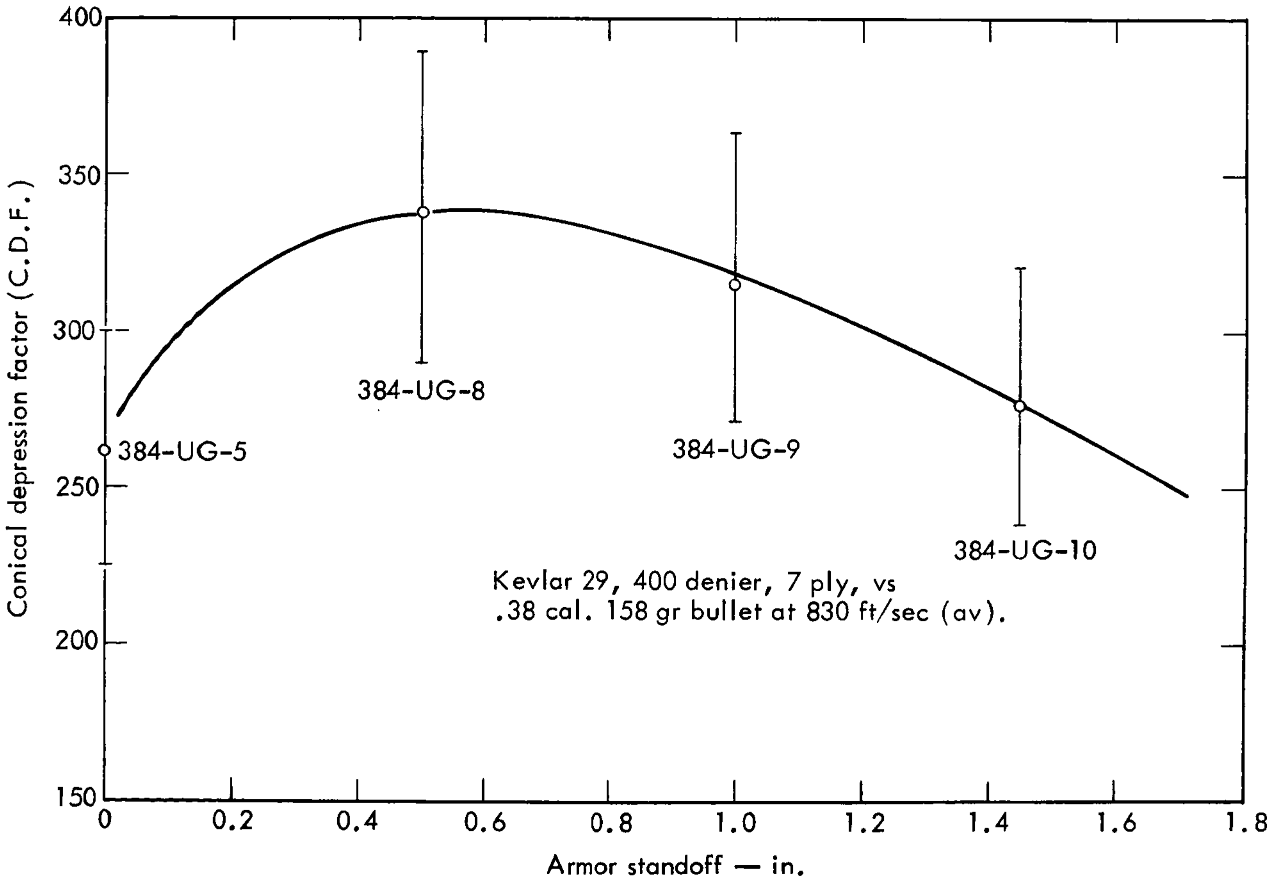
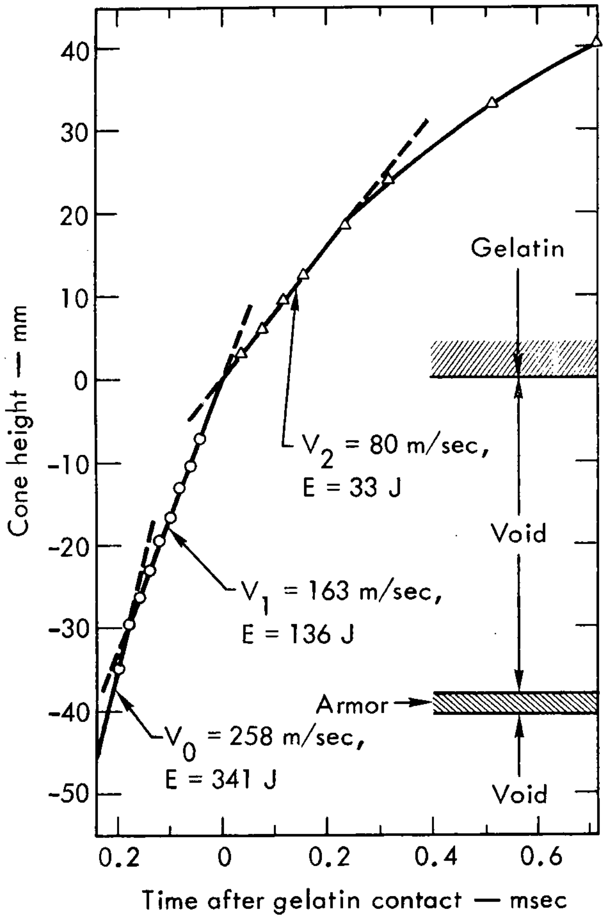


Fig. 16. Effect of armor standoff on the conical depression factor (C.D.F.). See Table 2, Group II.



GROUP IV

Test Group IV studied the effect of the armor ply count on the .22-cal., 37 gr. bullet. The bullet velocity was approximately 1055 ft/sec (standard muzzle velocity). The cone height, base diameter and time to 5% impact velocity were derived from the curves in Figs. 22 and 23, and the C.D.F. was calculated and plotted against the ply count shown on Fig. 13. The low C.D.F. values are logically spaced and, except for the low ballistic penetration limit for .22 calibre bullets, there were no surprises in this series.

Fig. 17. Bullet velocity and kinetic energy distribution for shot 384-UG-10. Standoff 1.5 in., mass 10.24 g.

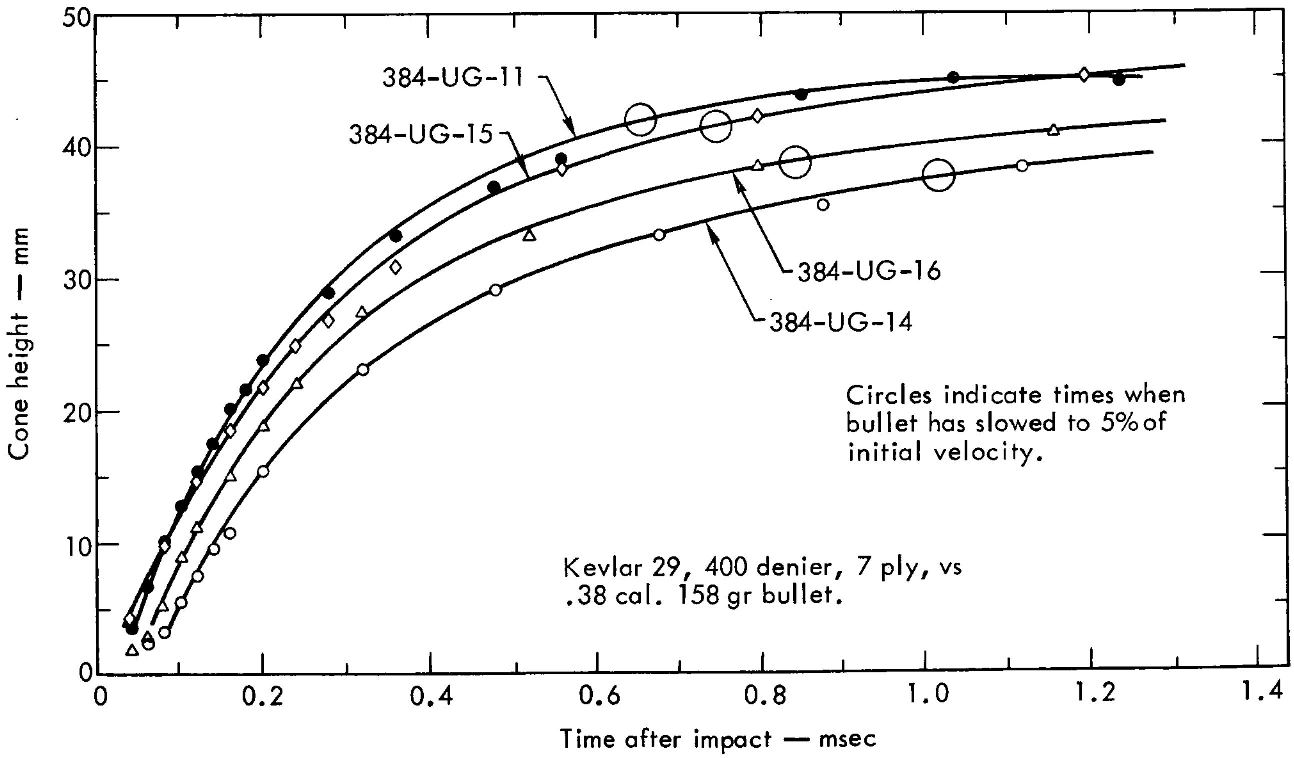


Fig. 18. Effect of projectile velocity on cone height. See Table 2, Group III.

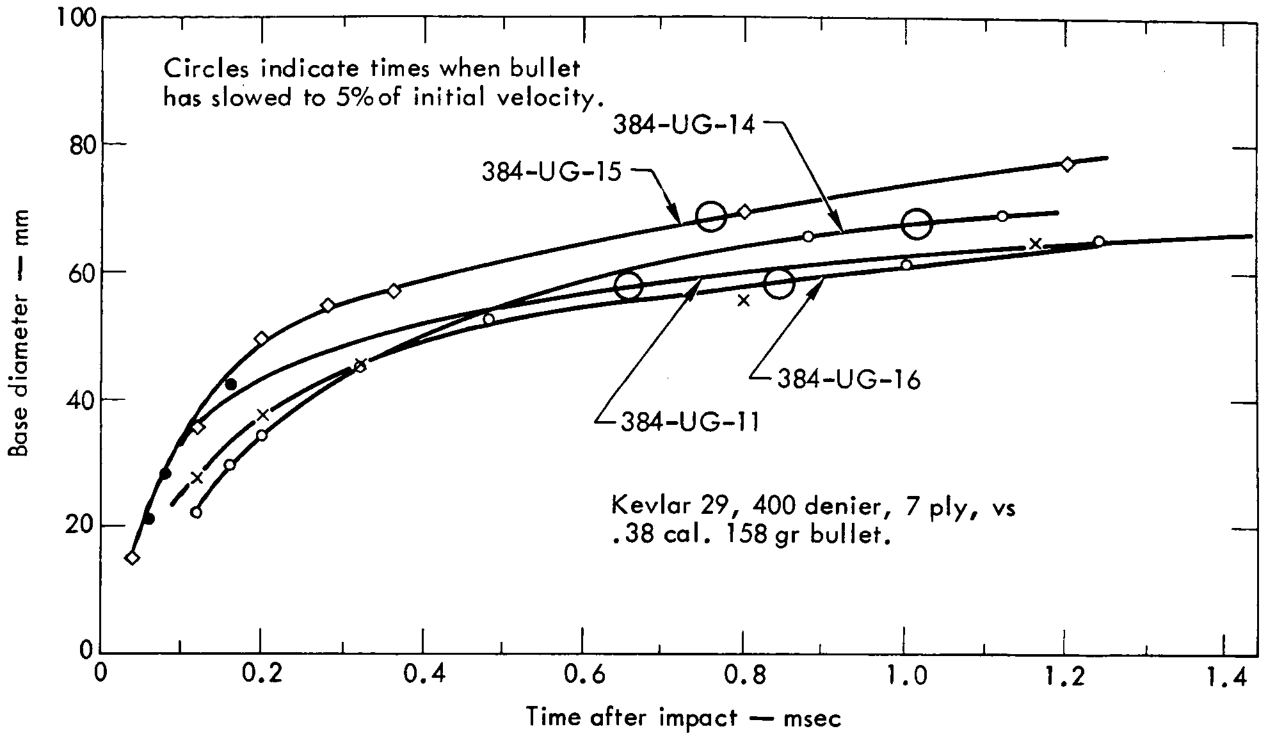


Fig. 19. Effect of projectile velocity on cone base diameter. See Table 2, Group III.

GROUP V

Group V was a study of the effect of the armor ply count on the 9 mm fully copper-jacketed, 115-grain bullet. Figures 24 and 25 show the effect on the C.D.F. parameters when the ply count is changed from 18 to 23. This is only a 28% difference in thickness and armor weight. Differences in ballistic effects seem somewhat insignificant and this is indicated when the 18 ply shot (384-UG-17) is plotted on Fig. 13. The other curves seem to flatten considerably after 16 or 18 plies. Even though the results are mixed, it seems that a curve through these 9 mm points would be within the error bars. Since the 9-mm and .38-calibre curves appear comparable on Fig. 13, the 9-mm bullet's ability to penetrate more plies might mean that the copper jacketing helps this bullet resist deformation and adds lubricity at the impacted interface.

If the weave were tighter and finer, the bullets might find it more difficult to separate the fibers and slip through the armor. Random weave orientation might reinforce the interstitial tacking or reduce it; this should be evaluated. Various coatings on the strands can also affect the ballistic performance.[7]

GROUP VI

Group VI was a study of the effect caused by a change in the cross-section of the impacting bullet when the target parameters and the bullet kinetic energy are held constant. The target was 16 plies of Kevlar-29 and the energy was approximately 340 J. Figures 26 and 27 show the curves used to establish the C.D.F. values for the .30 calibre and the

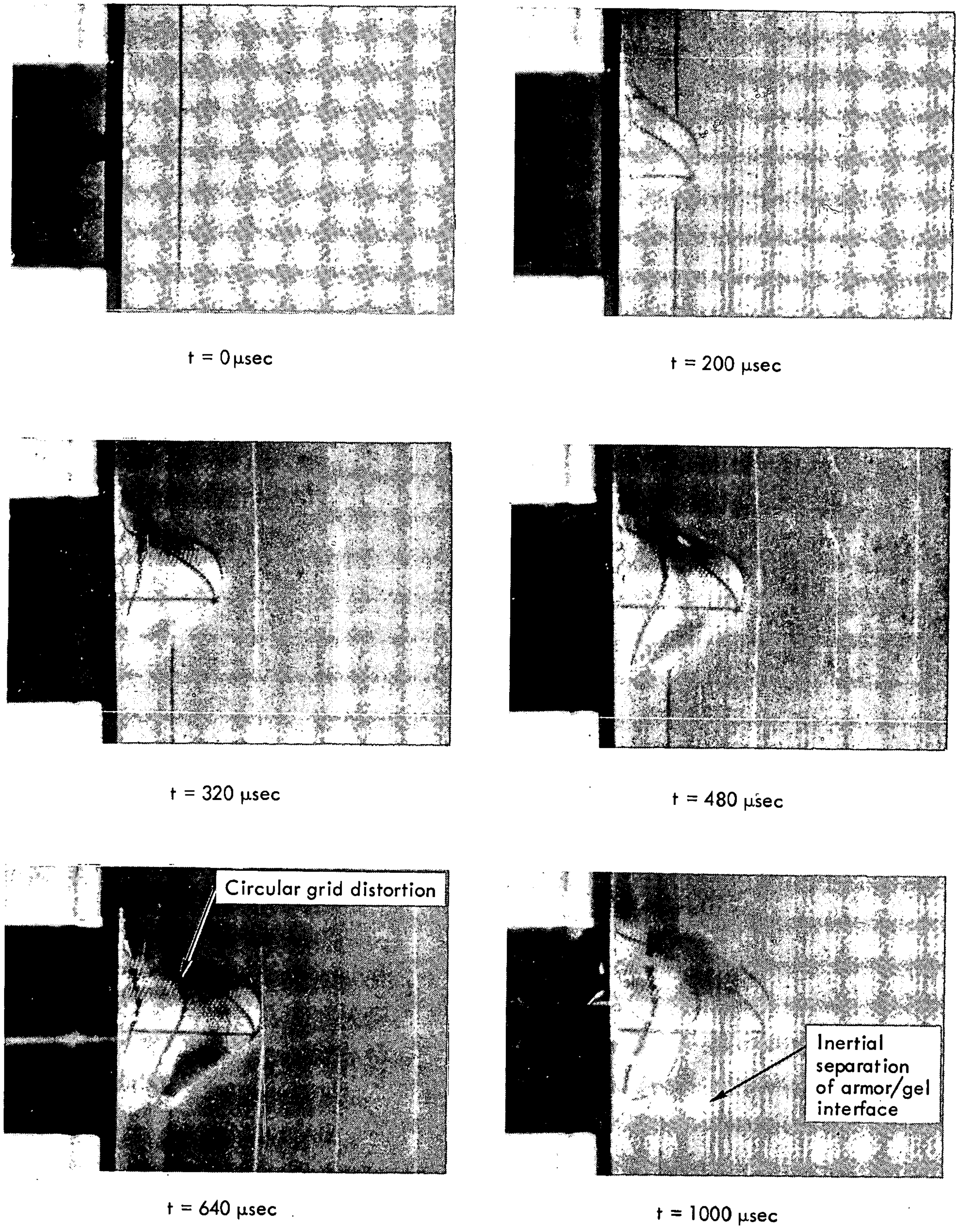


Fig. 20. Framing camera record from shot 384-UG-26.

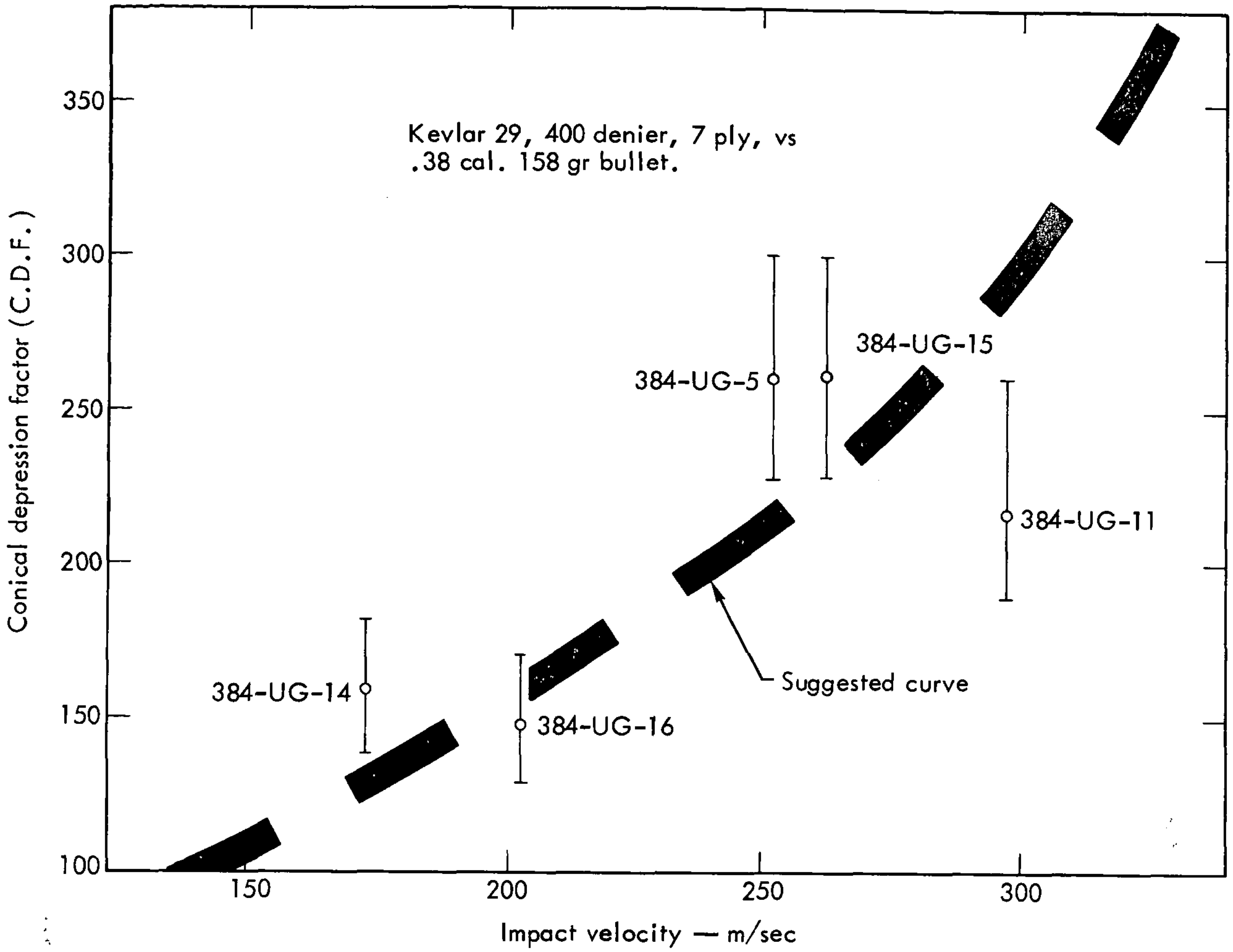


Fig. 21. Effect of projectile velocity on the conical depression factor (C.D.F.). See Table 2, Group III.

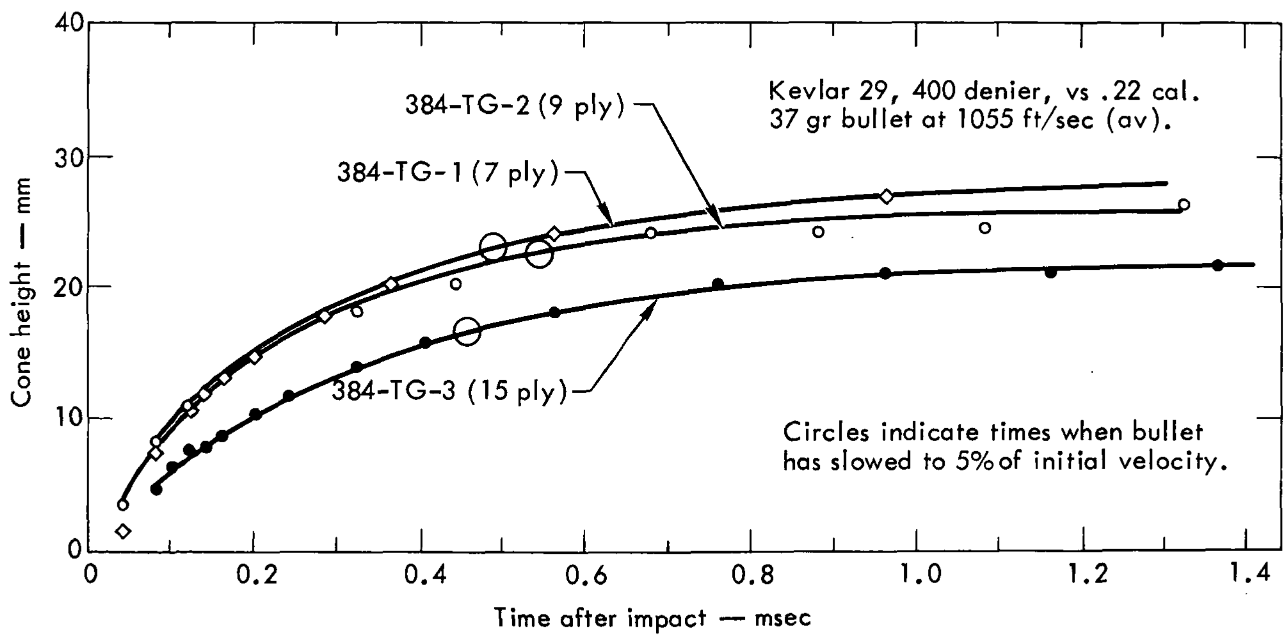


Fig. 22. Effect of armor ply count on cone height, .22 caliber bullet. See Table 2, Group IV.

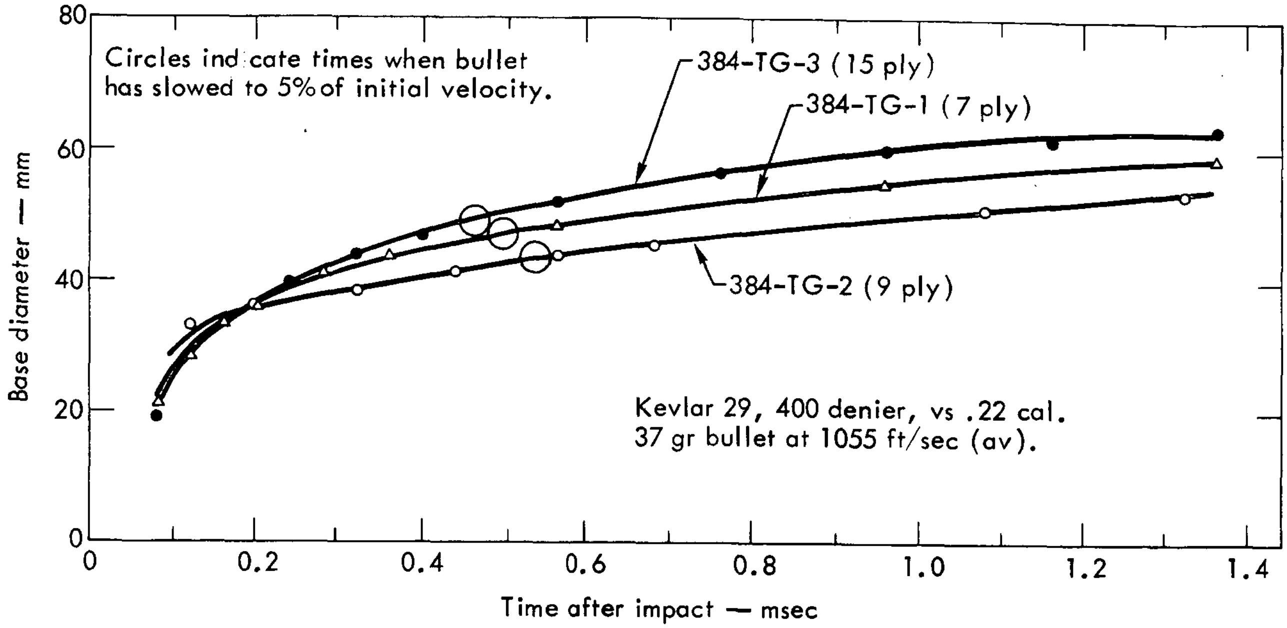


Fig. 23. Effect of armor ply count on cone base diameter, .22 caliber bullet. See Table 2, Group IV.

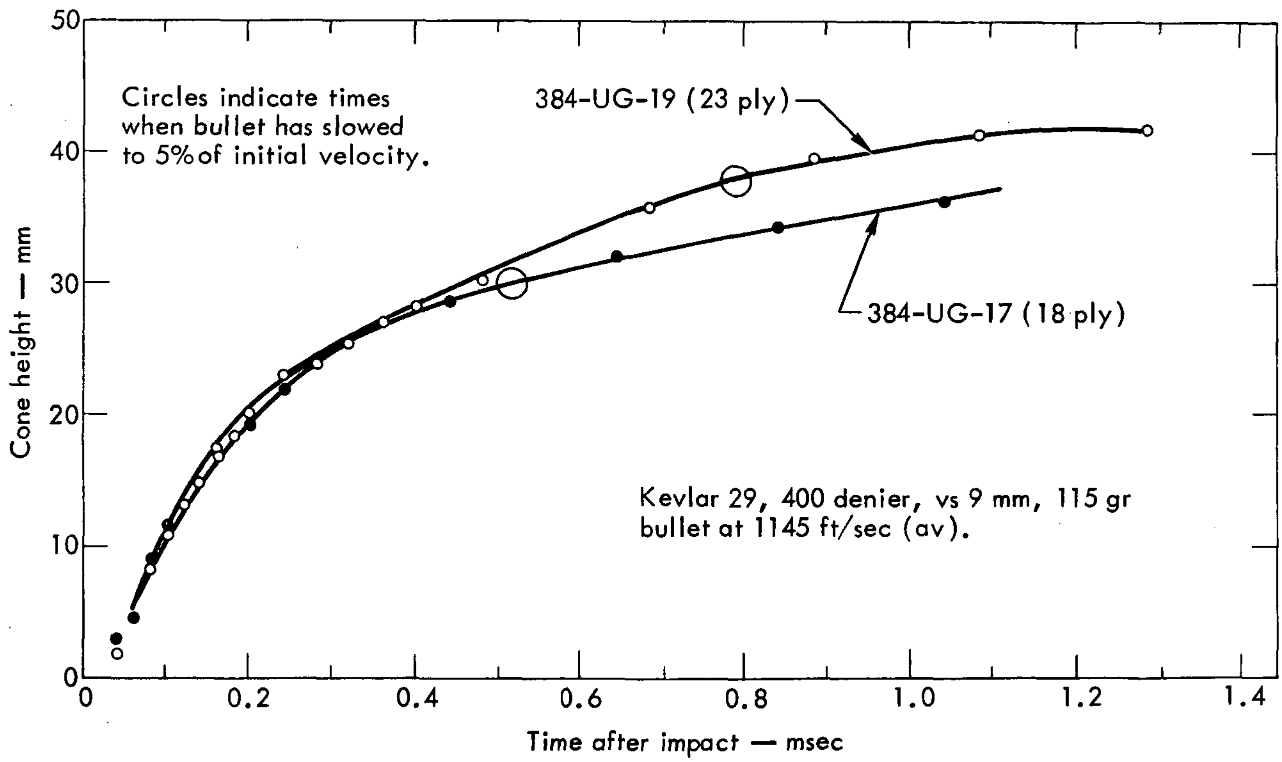


Fig. 24. Effect of armor ply count on cone height, 9 mm bullet. See Table 2, Group V.

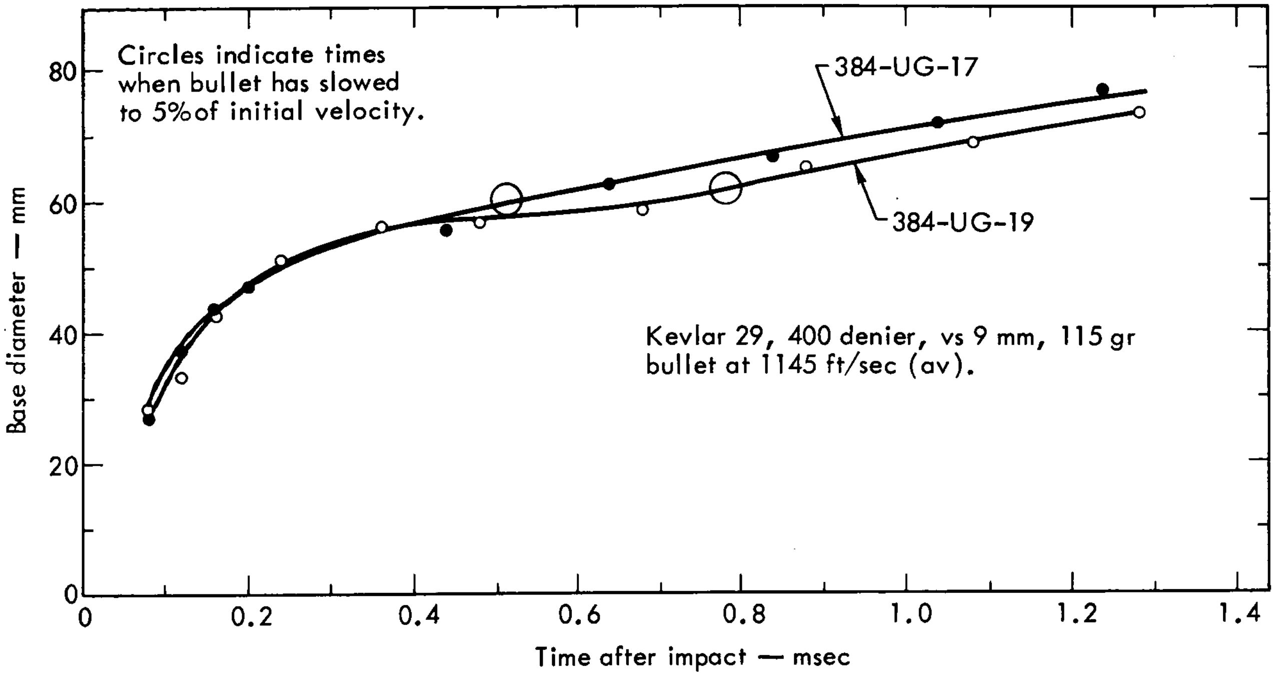


Fig. 25. Effect of armor ply count on cone base diameter, 9 mm bullet. See Table 2, Group V.

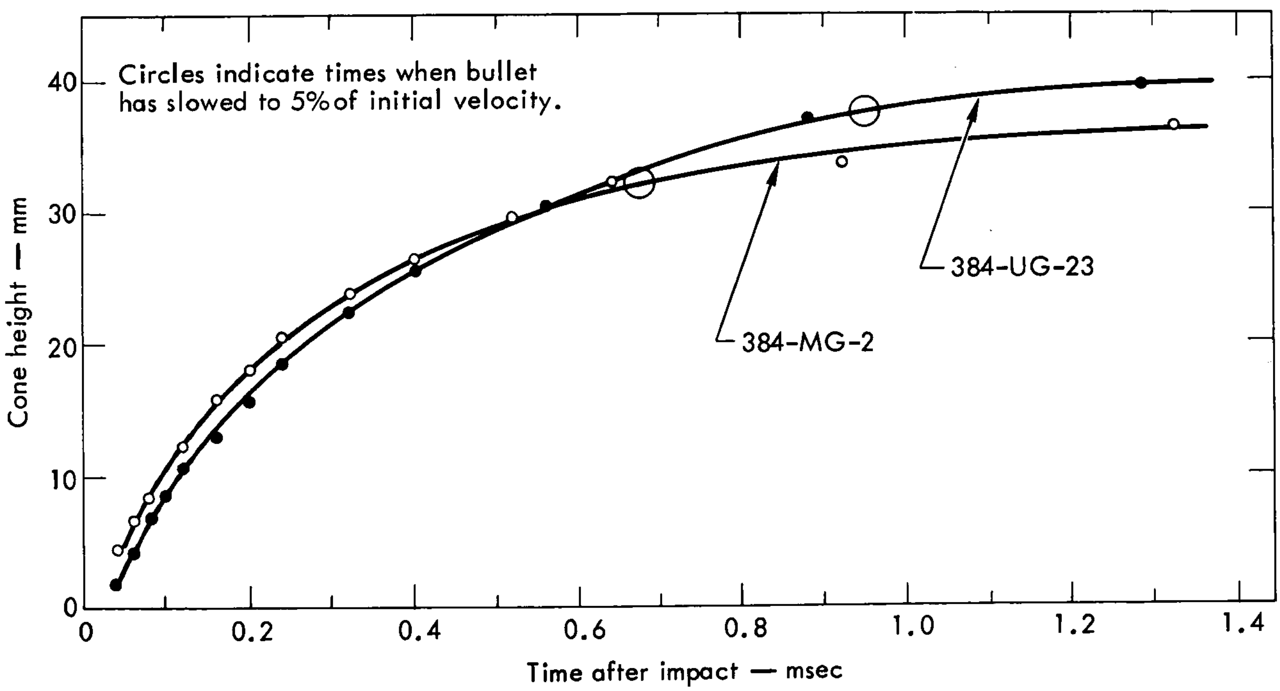


Fig. 26. Effect on cone height of lead bullet cross section at constant kinetic energy (340 J) on a common target. See Table 2, Group VI.

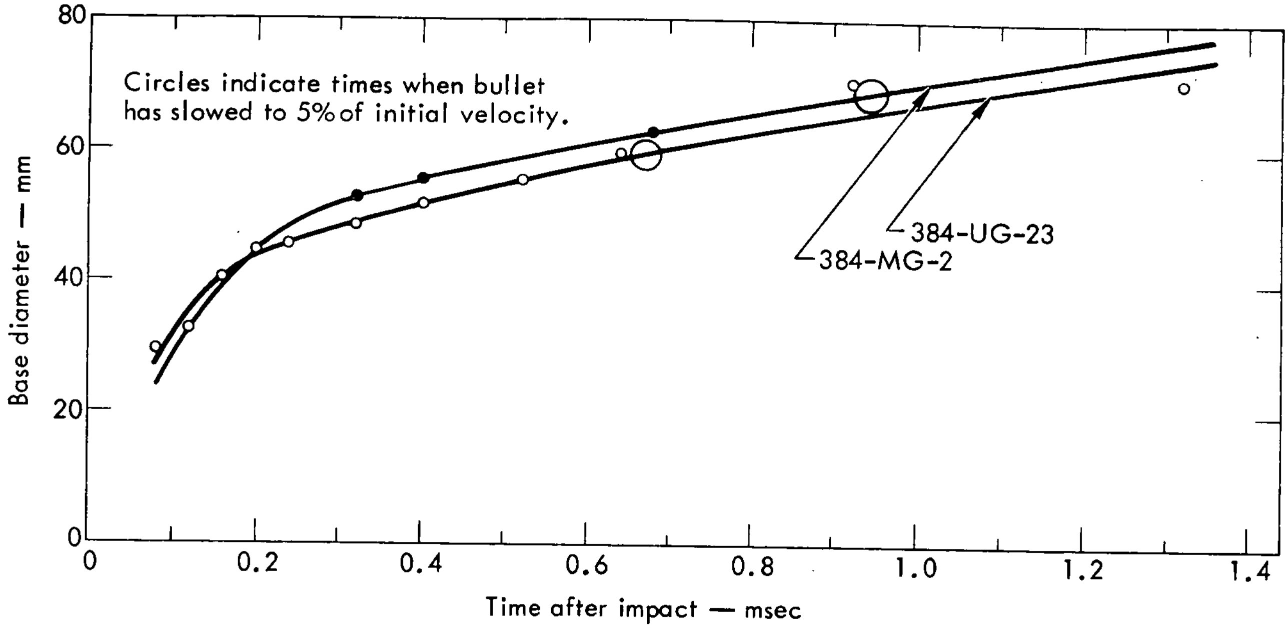


Fig. 27. Effect on cone base diameter of lead bullet cross section at constant kinetic energy (340 J) on a common target. See Table 2, Group VI.

.38 calibre shots. Unfortunately, the .22 calibre shot resulted in a full penetration. The curve in Fig. 28 indicates a possible dependence of the C.D.F. value on the bullet cross-sectional area.

Several bullet types are manufactured to fit most handguns. Varying a bullet parameter such as nose shape or material strength while holding the kinetic energy and the cross section constant creates a different curve. A family of curves based on bullet parameters can be generated to illustrate these differences. A designer could use such curves to specify more accurately his armor requirements.

SPECIAL GROUP

The ultra-high-speed camera systems available in the Vault 2 experimental area, in association with the high energy flash-lamp bank, make it possible to front light the ballistic event and study the surface features of the cratering phenomena. Two front-lit shots were completed; a few frames of each appear in Figs. 20 and 29. The film records contain approximately 60 frames each and lend themselves to ciné mode viewing. A 16 mm movie was created by copying these records.

Figure 29 shows the bullet impact from the front. A rhombic wave forms, moves out, and transforms into a rectangular depression. The deformation and rotation of the bullet can be observed, as well as the nonuniform lateral strain indicated by the grid distortion.

Figure 20 shows the view through the gelatine from the side. The contortion of the concentric grid circles suggests a depression pattern corresponding to that in Fig. 29.

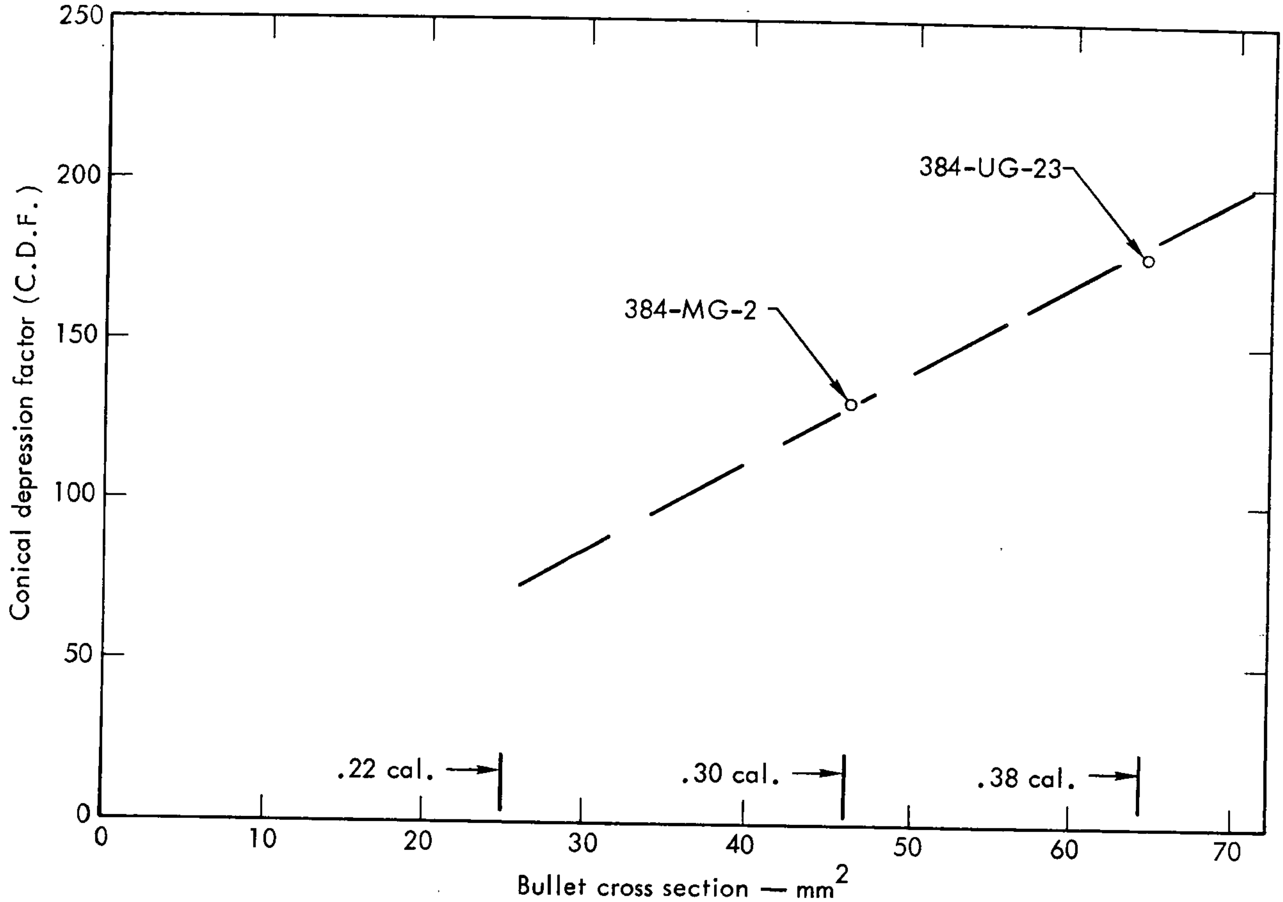


Fig. 28. **Effect** on conical depression factor (C.D.F.) of lead bullet cross section at a constant kinetic energy (340 J) on a common target. See Table 2, Group VI.

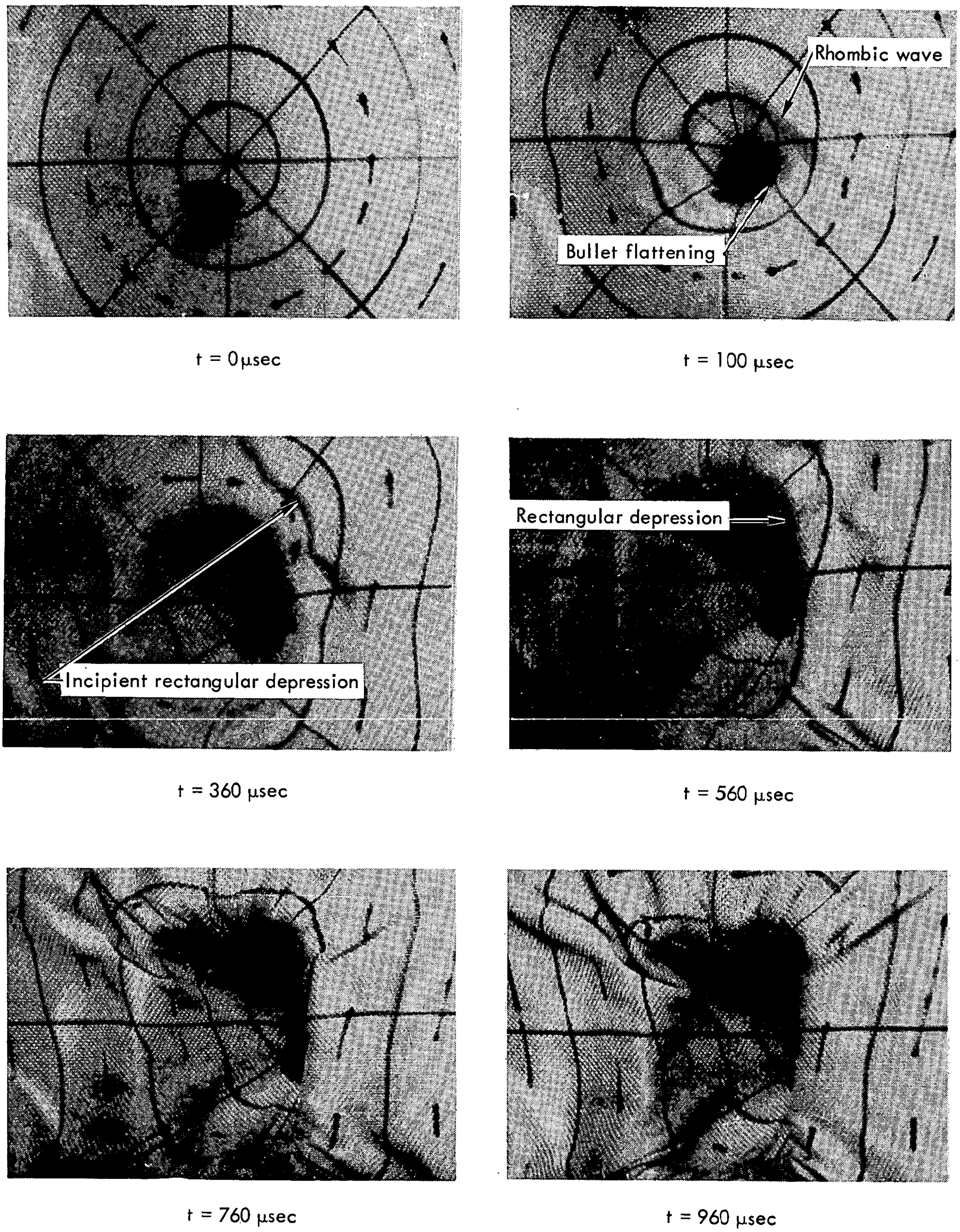


Fig. 29. Framing camera record from shot 384-UG-24.

Recommendations

In view of the many questions raised while working out this Test Matrix 1, the recommendations brought forth are broad and generalized.

A. A Laboratory effort should be funded for the ballistic study of soft armor materials. The effort should include:

1. Gelatin/animal tissue correlations.
2. Armor weave orientation.
3. Fiber surface treatments.
4. Composite armors.
5. Stand-off and undergarment effects.

B. Since these armor materials are rate sensitive,[7] most testing should be done on the ballistic range to avoid catastrophic extrapolations and miscalculations.

Acknowledgments

Thanks are due to the outstanding efforts put forth by the Vault 2 Firing Group. The firing range effort was headed by Doug Bakker, who also labored over the film-reading machine. The new guns were carefully prepared by Ivan Miller, who, with Doug Bakker, worked out the scheme for gelatin mixing. Butch Moyle designed the new velocity trap circuitry and followed the series through to completion.

Appendix A
Gelatin Preparation

(Doug Bakker/Ivan Miller Recipe)

A 20% gelatin mixture used at 10°C was recommended by the Medical Team at Edgwood Arsenal for the approximate mock-up for the human body under ballistic impacts.

Early attempts at LLL to produce optically clear gelatin block were stymied by unacceptable bubbling and darkening. Bakker and Miller worked out a technique using water at 60°C (hot tap setting). The powdered gelatin, Pharmagel A produced by Kind and Knox, is combined in the turbulence of a 1600 rpm mixer blade. No large lumps are produced and the color of the mix is a light-beer shade at the 8 in. thickness that was used. The foaming and large bubbles separate quite well within an hour after pouring the solution. Five drops of cinnamon oil improves the odor created by the spillage of the mix, and overnight storage in a 2°C refrigerator will barely bring the temperature of the gel block down to 10°C.

An immersion thermometer placed fairly deep in the gel block, but outside the impact reaction zone and photo area, monitors the temperature at shot time.

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RBC/lc/lm

APPENDIX E

IMPROVED PROTECTIVE ARMOR WEARABILITY TEST AND EVALUATION PLAN

Report No.
ATR-74(7906)-1

EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM

IMPROVED PROTECTIVE ARMOR WEARABILITY TEST AND EVALUATION PLAN

Law Enforcement Development Group
THE AEROSPACE CORPORATION
El Segundo, California

March 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

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

1.1 PURPOSE

The body armor wearability test and evaluation program is an integral phase of the improved protective armor development program. The purpose of this evaluation effort is to investigate the comfort, maneuverability, and appearance of typical garments as tested in an operational and controlled environment. The results of the tests will be used to establish specifications and requirements for future garment development and major field evaluations of protective garments. These are the overall objectives of the test activity:

- Evaluate the appearance of integrated and nonintegrated body armor garments relative to conventional uniforms and garments.
- Evaluate the maneuverability of law enforcement officers with and without armor garments under a variety of scenarios.
- Determine the degree of personal comfort of officers under different operating conditions when wearing typical garments.
- Obtain data on the acceptability/nonacceptability of soft body armor to various functional elements of the law enforcement agencies.
- Evaluate any degradation of the garments and protective material under operational conditions.
- Develop preliminary training aids in the wear, use, and care of body armor garments.

1.2 SCOPE

The test program will be conducted in widely separated geographic and climatic areas. Tentative sites selected include:

New York City, New York
Jacksonville, Florida
Los Angeles Basin, California

Two types of tests will be conducted. In each of the three major metropolitan areas the emphasis will be on operational wearability test and evaluation. This series of tests is the subject of this planning document.

Two types of garments will be fabricated for test purposes. The first is identified as the nonintegrated type which is typically represented by an undershirt design. The second is the integrated type where the ballistic material is incorporated into a standard garment such as a sport coat or uniform. Sufficient garments will be provided to obtain the wearability characteristics of each type under typical operating conditions.

> There is no intention to obtain data on the protective characteristics of the garments since tests on protective and environmental properties have not been completed. Statistically, the sample size is such that it is calculated that the probability of assault on an officer while wearing the garment is very small.

Figure 1 shows the activities to be accomplished in the test program and the responsibilities of the organizations involved.

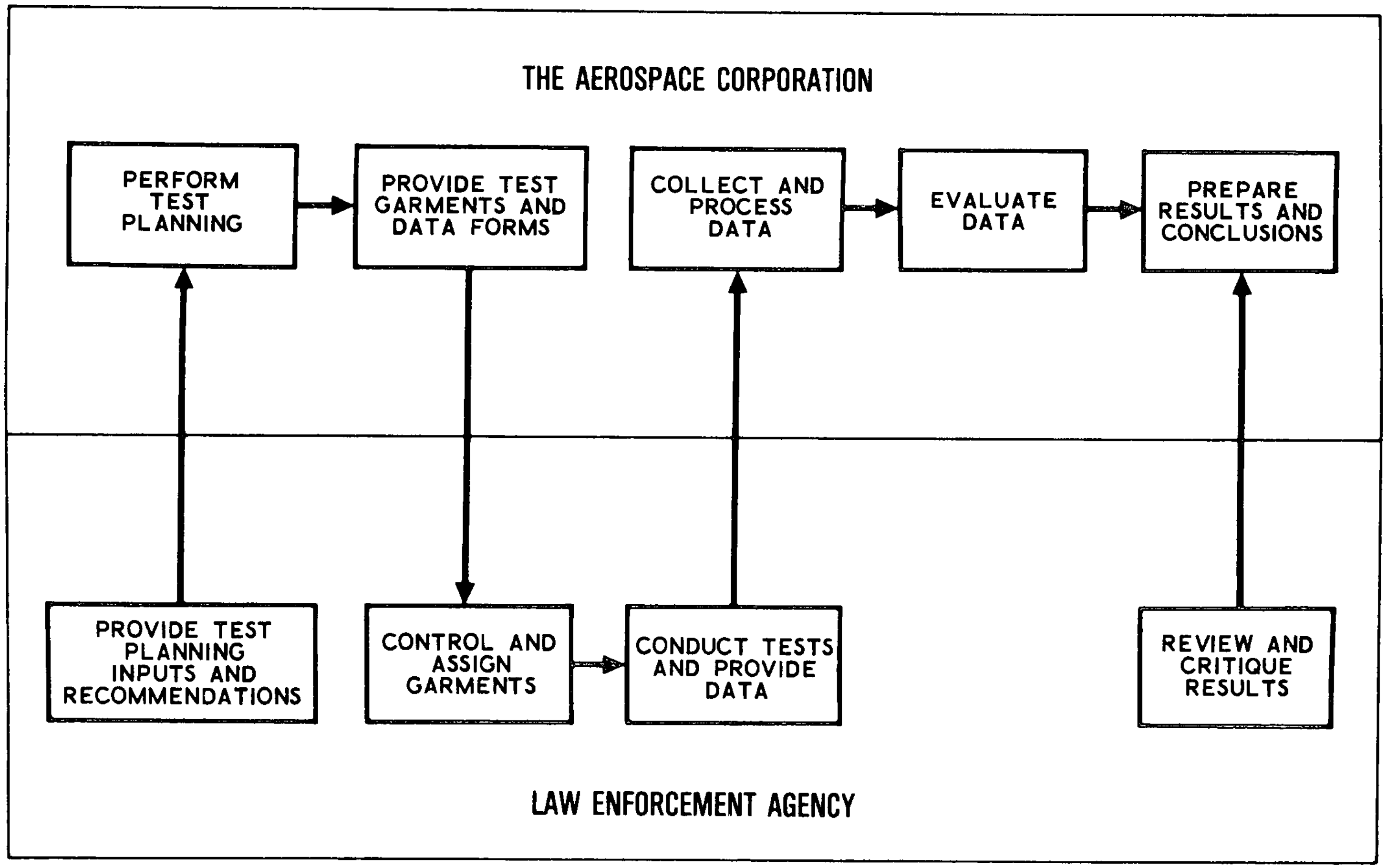

Figure 1. Test Responsibilities

2. BACKGROUND

In September 1972, The Aerospace Corporation, under contract to the National Institute of Law Enforcement and Criminal Justice of the Law Enforcement Assistance Administration (LEAA), initiated a program to develop protective garments. The objective of the program was to develop lightweight garments for public officials which were comfortable and relatively inconspicuous. In July 1973, a follow-on program based on the public official garments was implemented to consider law enforcement personnel subject to assault with firearms (handguns) or cutting weapons.

A review of assault, injury, and fatality cases within the law enforcement community indicated that the majority of assaults which resulted in death or serious injury were accomplished with handguns. A review of data from the FBI, International Association of Chiefs of Police, and metropolitan police departments indicated that handgun assaults with the threat severity of a .38 caliber police special or less comprised a large fraction of the recorded attacks. It appeared, therefore, that protection against the .38 special threat would significantly reduce fatal and serious injury assaults.

The Aerospace Corporation initiated an investigation through the U.S. Army Land Warfare Laboratory to perform ballistic evaluations on approximately 40 candidate materials and to test the blunt trauma effects on animals protected by ballistic materials. Of the materials tested, DuPont Kevlar, an extremely high-strength polymer, exhibited superior ballistic characteristics for penetration protection. Live goats were used to qualitatively test blunt trauma effects. Approximately 50 goats were tested with several Kevlar materials against the .38 and .22 caliber threat with no serious blunt trauma complications. Analytical efforts and additional testing with goats and other animals are continuing to obtain a more quantitative evaluation of the potential blunt trauma effects on humans.

Meetings were held with a number of law enforcement groups to define general guidelines on the type and application of protective garments.

In addition, meetings were held with yarn manufacturers, cloth weavers, and garment manufacturers on the feasibility of fabricating protective garments from Kevlar.

Prototypes of two basic garment types which incorporated this material have been successfully fabricated. In the integrated garment type, the ballistic material is incorporated as either a zip-in liner (leather jacket, car coat, etc.) or is fabricated into the garment (scooter coat, sport coat, etc.). The nonintegrated garment type is characterized by the undershirt or vest. The undershirt is designed for continuous inconspicuous wear while the vest may be slipped on in times of identifiable or potential emergencies. The prototype garments have been worn by several local police representatives, resulting in some minor redesign.

The wearability test and evaluation program discussed in this planning document is designed to be a further step in the development of acceptable lightweight body armor. The results will provide the basis for the specifications for and fabrication requirements for protective garments in the follow-on field evaluation program. It is planned to distribute approximately 5000 garments to a number of law enforcement agencies throughout the country for the conduct of a six- to 12-month operational field evaluation.

Figure 2 presents a functional flow of the total body armor program. The program has been structured to provide a logical progression from conception through system demonstration and to profit from the knowledge and experience of both law enforcement agencies and the armor industry in its planning and execution. Through the cooperation of these agencies it is anticipated that the resultant garments will be acceptable to them for operational use and that the garment will be technically capable of providing the required level of protection.

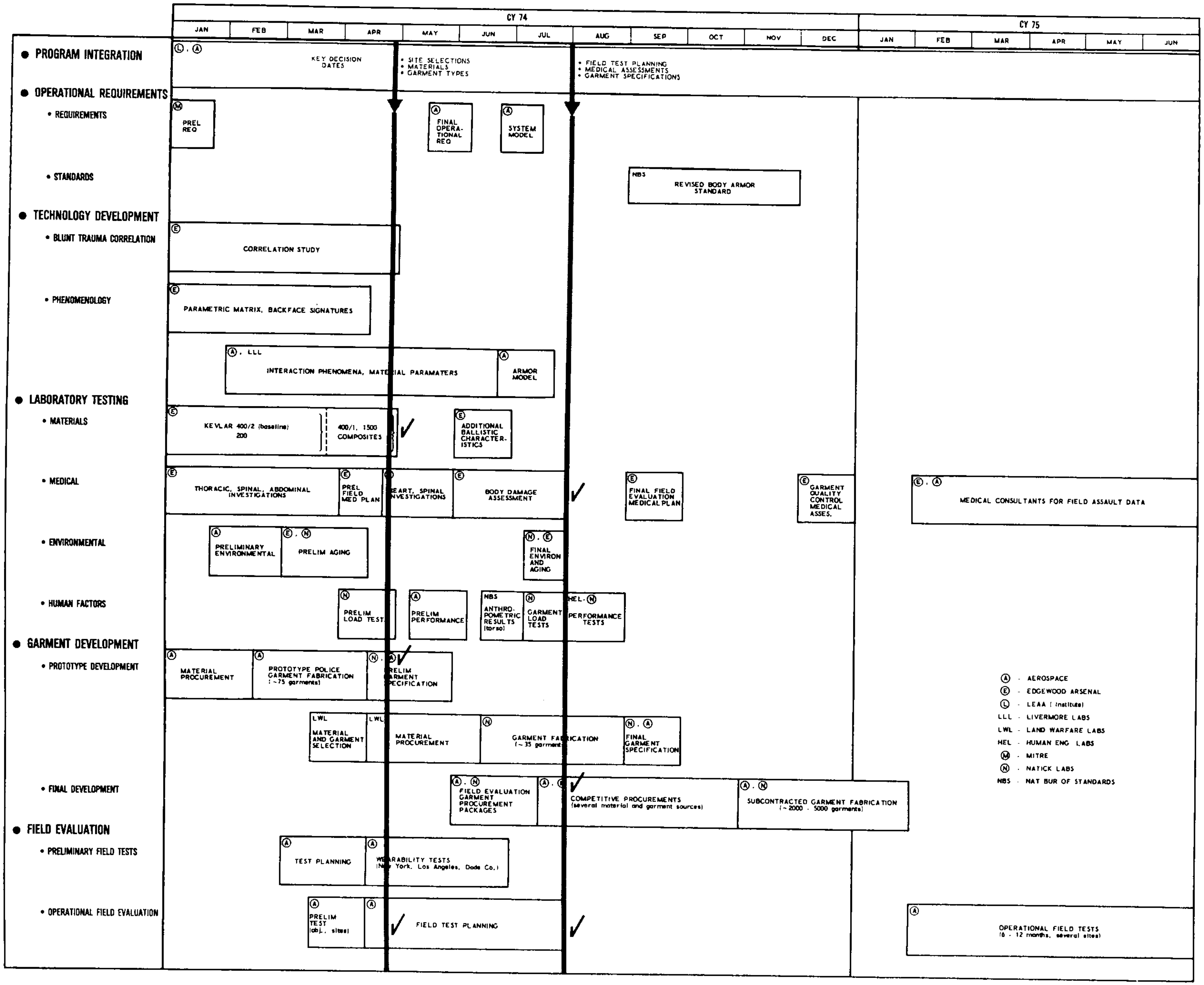

Figure 2. Body Armor Program Overview

3. TEST PLANNING CONSIDERATIONS

3.1 OBJECTIVES OF THE OVERALL BODY ARMOR PROGRAM

The number of felonious assaults on law enforcement and public officials have demonstrated a continuous increase over the past decade. Between 1960 and 1970, police fatalities increased at an average rate of over 14 percent per year. The body armor program is designed to provide equipment to reduce the number of fatalities and serious wounds to public officials from these assaults.

Although there are a number of protective devices on the market, they have been generally characterized as conspicuous, bulky, and uncomfortable for anything more than short-duration wear. Since the statistics demonstrate that the majority of felonious assaults are generally unexpected, it is highly desirable that the protective material be in the form of comfortable and inconspicuous wearing apparel.

Within this context, the overall LEAA program objectives may then be simply stated: to develop protective garments for use by public officials and law enforcement officers which are inconspicuous, inexpensive, and adaptable to a number of clothing needs.

3.2 TEST PROGRAM INTERACTIONS

As noted previously, Figure 2 shows the relationship among the various program elements. This section discusses the rationale for the wearability test program and its relationship to the other development tests and the follow-on field evaluation program.

The initial tests conducted in FY 73 were designed to demonstrate concept feasibility and to select the most appropriate material. FY 74 activities are designed to develop detailed technical data under controlled conditions. Particular emphasis is being placed on evaluating blunt trauma effects and on developing tools whereby these effects can be extrapolated from animal and/or laboratory tests to the human body.

In the latter part of FY 73 and FY 74, a number of prototype garments were fabricated whose design was based on requirements from various law enforcement groups. These garments have been exhibited to a large audience of law enforcement personnel and their comments have been noted. Only a limited number of garments have been subject to field operations and then only on a limited basis. The wearability test and evaluation program is therefore structured to obtain operational personnel evaluation of the garments for a larger sample. This program will then provide the data base for the fabrication of the approximate 5000 garments to be employed in the field evaluation program and will ensure that maximum comfort has been built into them.

3.3 AREA CONSIDERATIONS

Although the number of garments available for the wearability tests are severely limited, it is desirable to obtain as broad a variation in climatic, geographic, and uniform styling conditions as possible. New York City, Florida, and Southern California were recommended by LEAA.

New York presents the extremes in climatic conditions. Summers are hot and humid with additional temperature load contributed by both the lack of undeveloped areas and the high-rise building density. Winters are normally cold and damp.

Florida has a relatively stable climatic situation. Temperature variations are small from summer to winter with a constantly high relative humidity. Garments worn the year around by law enforcement personnel are relatively light in weight.

The Los Angeles Basin was selected on the basis of two considerations. First, seasonal temperature variations are not high, but in the summer months temperatures in the high 90's and low 100's are experienced. These high temperatures are normally associated with low humidity. Also, diurnal variations of 30° to 50° are not uncommon. Second, the city Police Academy has a nearby controlled test area and a number of departments run operational simulations at Universal Studios. These two locations can provide the facilities for the development of training aids.

3.4 GENERAL TEST PHILOSOPHY

The general test program is designed to obtain data on two critical aspects of the improved protective armor. They are the comfort of the garments under continuous wear in typical summer climatic conditions and the assessment of the wear characteristics of the garments under operational conditions.

The evaluation of the comfort of the garments will be based on data obtained from the participants. These data will be collected both through forms completed by the users and, where possible, by use of direct interviews. Comfort will be assessed on the basis of general feel of the garment, coolness, and hindrance both in normal wear and in typical operational situations (interviews, interrogations, traffic violations, arrests, pursuits, stake-outs, etc.). These data will be correlated with the attitudes and physiological characteristics of the user to obtain additional design information.

Because of the short duration of the tests, only limited information is expected on the wear characteristics of the garments. However, both during and at the conclusion of the tests the garments will be inspected for abnormal wear indications. Factors to be considered will include but not be limited to: bunching of the ballistic material; points of high stress on the basic fabric, seams, or fasteners caused by the stiffness of the material; wear or stretching of the material or garment; obvious changes in appearance; and bleeding of the material caused by moisture or perspiration.

During the test period, control and maintenance of the garments will be the responsibility of the individual officer or the participating department, depending upon the individual case. At the end of the test program, all garments will be returned to The Aerospace Corporation for post-test inspection and evaluation.

3.5 ANALYSIS AND EVALUATION

The analysis and evaluation portion of the program is designed to extract both subjective and quantitative data which will be used to improve the wearability of future garments.

During the test program, the main vehicle for data collection will be prepared forms provided to each agency participating in the tests. These forms are designed for rapid recording of data so that a minimum of time is required by the participants.

For those factors which can be quantified, a weighted variable evaluation technique will be employed by Aerospace with values assigned to both the independent and dependent variable. In those instances where the factors are a function of the judgment of the participant, they will be weighted on the basis of his attitude and physiological make-up. This approach will tend to normalize the result to a statistical mean.

4. TEST APPROACH

As stated previously, the objective of the test program is to obtain data on the wearability of selected garments under operational conditions. Statistically, it is not anticipated that a firearm or knife assault on an officer will occur during the program.

4.1 GARMENT DEFINITION

For each locale, a number of garments will be fabricated with ballistic material to the specifications for each area. Every attempt will be made to ensure that outer garments with body armor are identical in appearance to the same garments without the ballistic material. Table 1 shows the number and types of garments to be provided in each area.

Table 1. Test Garment Distribution

New York		Jacksonville		Los Angeles Basin	
No.	Type	No.	Type	No.	Type
1	Reefer Coat	6	Sport Coats	4	Vinyl Jackets
1	Summer Blouse	6	Dress Vests	2	Leather Jackets
2	Leather Jackets	4	Undershirts	4	Undershirts
6	Scooter Coats	4	Short Vests	3	Short Vests
4	Undershirts	2	Body Shirts	2	Body Shirts
4	Short Vests	3	Long Vests	3	Long Vests
2	Body Shirts				
3	Long Vests				

4.2 GARMENT TESTING

Garments selected for wearability testing represent the majority of those worn by the police in each locale. The attempt has been made, within the limitations of the number of garments, to obtain a representative sample based on discussions and inputs from the appropriate divisions within each agency. Standard garments have been emphasized in order to obtain maximum wear during the test period. It is desired that records be maintained on the participants wearing the garment on both a weekly and by incident basis.

During the test program, a data base will be developed against which the analysis and evaluation will be performed. In the operational tests, specific data will be collected against which each test objective can be assessed. Table 2 summarizes the test objectives, the data to be collected, and the method of recording the data.

Appendix I contains sample forms of the type to be used for recording data during the test program. The main source of data will be the forms completed by the participants and collected by the department. Prior to the test, a briefing and demonstration will be given to the participants on the objectives, conduct of the test, and planned follow-on activities. Also, at this time an interview will be held with each participant. At selected times during the test program, in-process reviews will be held with the participating agencies. The purpose of these reviews will be to ascertain the test program progress; collect and review preliminary data; identify, discuss, and resolve any problem areas; review and coordinate on future plans; and provide the vehicle for transfer of findings from one test area to another. These reviews are desired monthly during the course of the test program. A final review will take place at the conclusion of the data analyses and evaluation task to provide each participant with the aggregate findings and results of the total program. Support will be solicited from all participants in terms of future activities and recommendations on the fabrication and use of the garments, and to assist in the planning for the follow-on, large-scale field evaluation program.

Table 2. Operational Test Data

Test Objectives	Data Required	Method of Recording
Evaluate garment in terms of hindrance during running and pursuit	No. of occasions required to run Nature of the incident Description of critical obstacles Effect of protective garment	Participant will record observations on appropriate form at completion of shift
Evaluate participant in subduing adversary or other arrest situation	No. of occasions required to subdue or arrest Inherent difficulty of the situation Effect of garment on ability to perform Cause of increased difficulty (if appropriate)	Participant will record observations and conditions on appropriate form at completion of shift
Determine attitude of the participant on weapon access	General feeling concerning weapon access Specific incidents where access was required Observations pre- and post-incident	Participant will record observations and incidents on appropriate form at completion of shift
Determine attitude of the participant toward body armor in general and soft body armor in particular	Psychological attitude toward body armor before, during, and after test	Interviews with participants Note: It is expected that there will be some correlation between attitude and age, years on force, and previous experience

Table 2. Operational Test Data (Continued)

Test Objectives	Data Required	Method of Recording
Determine mobility of participant during rescue operations	No. of rescues attempted Nature (description) of rescue operation Controlling conditions of operation Effect of garment on performance of duties	Participant will record observation and conclusions on appropriate forms
Obtain data on comfort of garment	Weight compared to similar garments and weight distribution Comparative ease of putting on or taking off garment Effect of ballistic material on garment fit Identification of points of chafing or abrasion Ability to retain or diffuse heat General comfort compared to standard garments Factors which make the garment uncomfortable Willingness to wear garment Factors which hinder wearer during normal activities	Observation of participant, duty assignment, and shift assignment recorded on appropriate form General data on participant recorded on general data form Weather data obtained from local weather bureau

Table 2. Operational Test Data (Continued)

Test Objectives	Data Required	Method of Recording
Obtain data on comfort of garment (cont'd)	Time worn/not worn and reasons for not wearing Weather conditions a. Temperature b. Humidity c. Wind (speed) d. Cloud cover e. Precipitation Duty assignment and shift	
Obtain data on the degradation of the garments under conditions of operational wear and maintenance	Periodic inspection of garment during test phase Identification of abnormal wear or material failure caused by ballistic material Ballistic evaluation at conclusion of test program	Written assessment of garment performance during test Ballistic tests of selected garments subsequent to completion of operational tests with emphasis on penetration resistance and energy absorption relative to new material
Define the requirements for training aids in the use and mainenance of garments	Problem areas and/or deficiencies noted during operational tests	Video tape Motion pictures Still pictures Written and illustrated training material

4.3 GARMENT CARE

A series of experiments are being conducted by Aerospace and the Army to evaluate the effect of laundry and dry cleaning agents on the ballistic characteristics of Kevlar. As a preliminary measure, dry cleaning cycles should be avoided or kept to a minimum. Where the ballistic material is in the form of a zip-in lining, or otherwise removable, it should be removed before cleaning. In the undergarments, where possible, the ballistic material should be removed before laundering. Otherwise, laundering should be done in cold water with Woolite. Oxidizing agents must be avoided. Under no conditions should liquid or powdered bleach, hot water or harsh detergents be used in laundering the garments with the ballistic material in place. The normal wash cycle should be used and the garment dried in a dryer using the air cycle (no heat) setting for delicate items. Drying should be conducted for at least one hour.

4.4 TEST RESPONSIBILITIES

The two key participants in the test program are the local law enforcement agencies and The Aerospace Corporation.

4.4.1 The Local Law Enforcement Agency

Each agency will assist in the planning of the detailed conduct of the test program. This will consist of participation in selection of garment types, identification of participants, assignment of garments to precincts or special forces to the individual level, monitoring the use of garments, dispensing and collecting of data forms, identification and clarification of unusual incidents, maintenance of the garments, and review of program progress and findings. In addition, the departments will participate in the in-process reviews and provide guidance in agency-unique problem assessment.

4.4.2 The Aerospace Corporation

The Aerospace Corporation is responsible for the overall test planning with inputs and support from the local agencies. It will subcontract the procurement of the test garments from approved or capable suppliers with, where possible, both uniform and armor experience. Aerospace will provide all data forms and participate in the pre-test, in-process, and post-test reviews with the local agencies. It will collect the data forms during the test program and perform the analysis and evaluation functions. Test results will be coordinated with and supplied to the participants in a timely manner.

5. ANALYSIS AND EVALUATION

This section discusses the methods to be incorporated by Aerospace in data analysis and evaluation. The information is presented so that the user may have an understanding of the types of analysis and evaluation being planned and which dictate the data forms being provided. Although the total evaluation will not be complete until approximately 60 to 90 days after the test period, preliminary results and observations will be made available as soon as conclusive evidence of a trend or result has been obtained. These results will be used to alert other test areas of potential or real problems or trends.

5.1 DATA ANALYSIS

The data used and the method of analysis will be a function of the individual test objective and the garment being evaluated. Table 3 shows the methods to be incorporated in the data analysis task as a function of the test objectives.

The data analysis task will be structured to convert the raw data by means of suitable processing techniques to a format which can be evaluated.

5.2 DATA EVALUATION

This section presents a set of typical data evaluation formats. No attempt has been made to provide a complete set but only to demonstrate how the collected information will be presented for final evaluation. Figures 3 through 6 show the format to be used for selected items of evaluation.

Table 3. Data Analyses

Test Objectives	Data Analyses
Evaluate garment in terms of hindrance to participant during running and pursuit	The analyses should include a weighting of the severity of the situation and the degree of hindrance under the conditions
Evaluate participant performance in subduing adversary or other arrest situation	The analyses should include a weighting of the severity of the situation and the degree of hindrance under the conditions
Determine the attitudes of the participant in terms of any feeling of degradation of access to weapons	The analyses should include a weighting of the severity of the situation and the degree of hindrance under the conditions
Determine the attitude of the participant toward soft body armor garments	These data will be used to modify or shade the reports submitted by each individual as a means of normalizing the data
Determine the mobility of participant during rescue operations	The analyses should include a weighting of the severity of the situation and the degree of hindrance under the conditions
Obtain data on the comfort of the garment	One of the key factors in garment comfort is the temperature/humidity index [$THI = 0.4\ (TBD + TWB) + 15$] $THI \geq 75$ majority of persons uncomfortable $THI \geq 80$ nearly all persons uncomfortable Correlation between THI, wear/nonwear, attitude, and psychological make-up of participant will be required. Temperature and humidity data should be obtained from the National Climatic Center

Table 3. Data Analyses (Continued)

Test Objectives	Data Analyses
Obtain data on the comfort of the garment (cont'd)	On a garment-by-garment basis, correlate the sources of discomfort, e.g., weight, ease of wear, tightness or constraint, chafing or abrasion points, duty assignment, ease of putting on and taking off
Obtain data on the degradation of the garment under conditions of operational wear and maintenance	Photographic records of garment prior to, during, and after test program Records of number of times ballistic material washed or dry cleaned and conditions Laboratory and ballistic tests on material after test program

EXAMPLE ONLY

TEST OBJECTIVE: EVALUATE GARMENT IN TERMS OF HINDRANCE TO PARTICIPANT DURING RUNNING AND PURSUIT

GARMENT: BODY SHIRT

SITUATION SEVERITY: FELONY IN PROGRESS - 20

TOTAL No. OF INCIDENTS = 33

TOTAL ACCEPTABLE PERFORMANCE = 28

% ACCEPTABLE = 85

POSSIBLE BIASED UNACCEPTABLE = 2

POSSIBLE BIASED ACCEPTABLE = 3

PROBABLE RANGE = 76% TO 91%

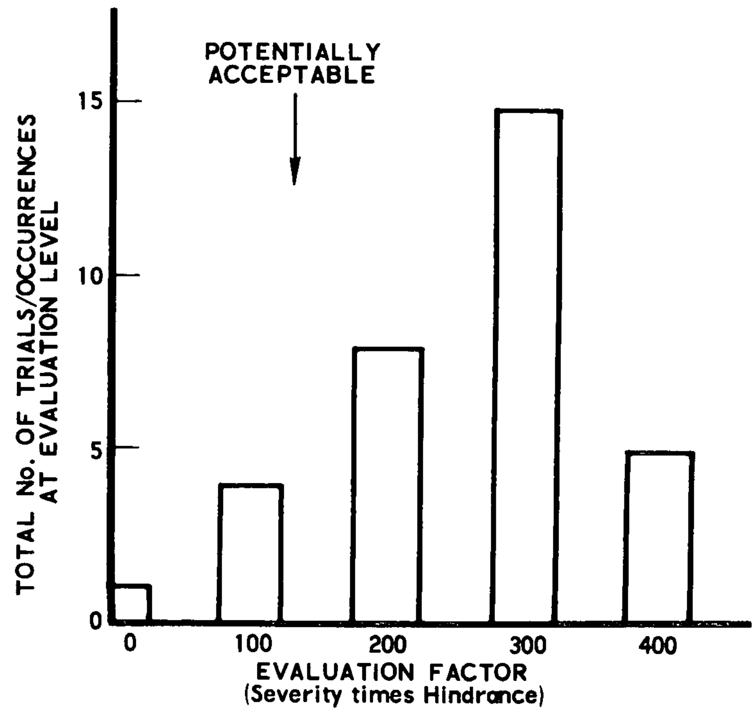

Figure 3. Evaluation During Running and Pursuit, Individual Case (Example Only)

TEST OBJECTIVE: EVALUATE GARMENT IN TERMS OF HINDRANCE TO PARTICIPANT DURING RUNNING AND PURSUIT

GARMENT: BODY SHIRT

SITUATION SEVERITY: COMPOSITE

TOTAL No. OF INCIDENTS = 91

TOTAL No. ACCEPTABLE = 65

TOTAL No. UNACCEPTABLE = 26

% ACCEPTABLE = 71%

EXAMPLE ONLY

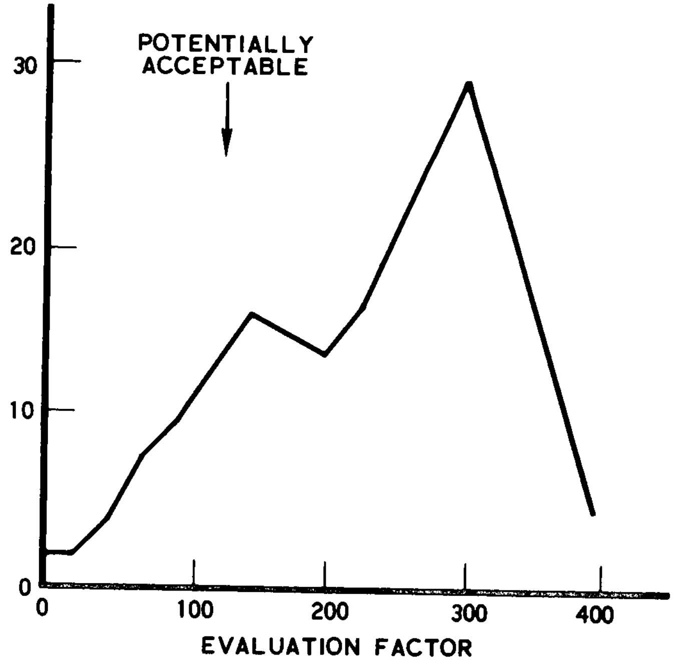

Figure 4. Evaluation During Running and Pursuit, Summary

TEST OBJECTIVE: OBTAIN DATA ON COMFORT OF GARMENT

GARMENT: BODY SHIRT

SITUATION: NORMAL CAR PATROL

EXAMPLE ONLY

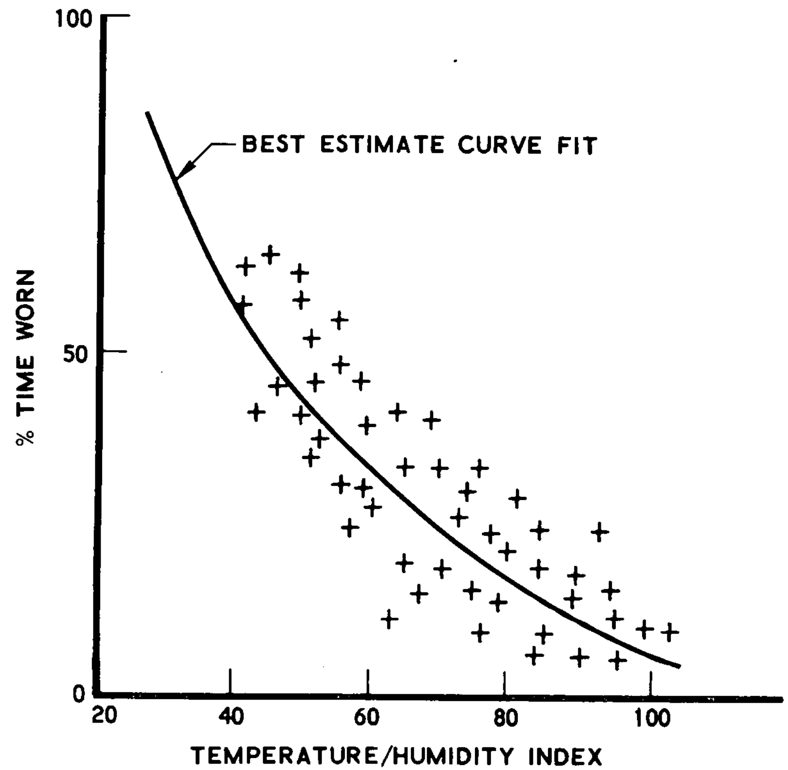

Figure 5. Comfort, Individual Garment

EXAMPLE ONLY

TEST OBJECTIVE: OBTAIN DATA ON COMFORT OF GARMENTS

GARMENTS: ALL (comparative)

SITUATION: NORMAL CAR PATROL

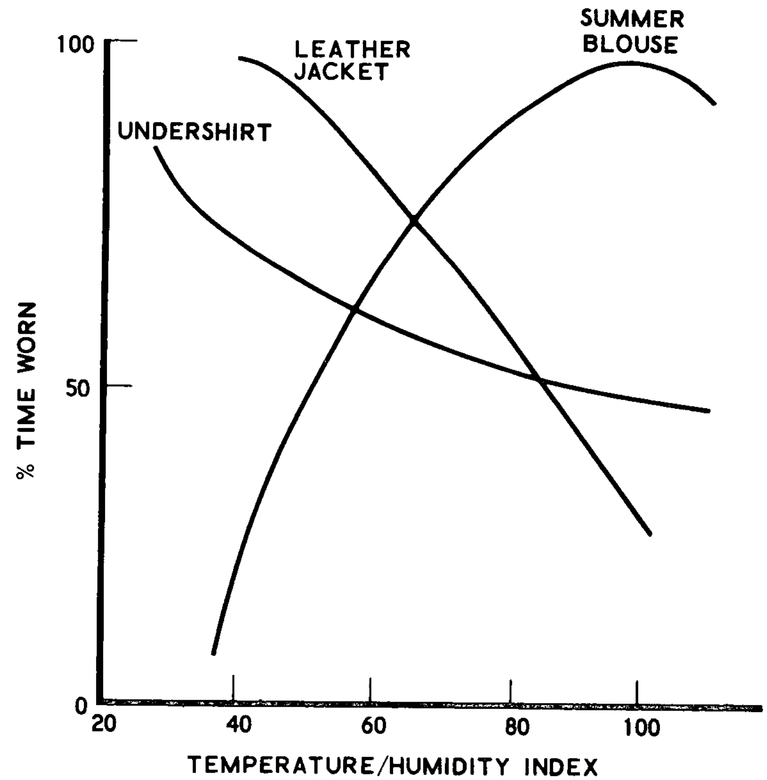

Figure 6. Comfort, Summary

APPENDIX I

TEST DATA FORMS

This appendix contains sample test data forms to be used in the test program. These forms are to be completed at the appropriate times in the program to provide the data base for analysis and evaluation. The following forms are provided:

Form W1	Letter to Participants and Sign Off Interview Information (to be completed at beginning of tests)
Form W2	Post-Test Addendum (to be completed at end of test)
Form W3	Weekly Data Form
Form W4	Incident Report Form (to be completed for each incident)

Although the statistical probability of a weapon assault during the test period is small, a finite possibility does exist.

TO ALL PARTICIPANTS IN THE BODY ARMOR WEARABILITY TESTS

On behalf of the Law Enforcement Assistance Administration (LEAA) and The Aerospace Corporation, we thank you for your willingness to participate in this body armor wearability evaluation.

The garment you have been issued is a prototype of a new development in lightweight body armor. This development was undertaken by the Law Enforcement Assistance Administration to provide improved personal protection to law enforcement personnel for a significant but limited handgun threat.

Data on assaults on law enforcement personnel have indicated that more than one-half of the guns used in these assaults have been of 38 special caliber or less. This garment has been designed to prevent penetration of bullets from weapons in this range.

A series of comprehensive tests has been conducted by U. S. Army Ballistic Laboratories to demonstrate the nonpenetration and protective qualities of the ballistic material contained in these garments. These tests have included the use of animals to ascertain the kind of tissue damage and blunt trauma effects that occur when a bullet strikes but does not penetrate the ballistic material. Although the ballistic material in these garments is designed to provide protection against the handguns listed below, the resulting bruises may be significant and will require a medical checkup.

.22 (1000 fps)	380
.25	38 special (800 fps)
.32	

The material will also prevent penetration of the 45 automatic; however, the blunt trauma effect could be serious if the wound is in a critical area (e.g., the liver, spleen, kidney, lungs or heart). The material will not provide protection against high energy handguns (e.g., 357 mag, 9mm, .44 mag, etc.) or against rifle fire which comprise less than one-fifth of available criminal weapons.

The garment you have been issued is a prototype or advanced model which may eventually be made available to law enforcement personnel through normal uniform or body armor sources. These prototype garments have been provided for the purpose of assessing their wearability only. As prototypes no claim is made for their protection capability other than the ability to prevent penetration of bullets from handguns of 38 special caliber or less, and no responsibility is assumed for any injury which may be sustained by a wearer.

Since you will be responsible for these garments for a period of two to three months, the following procedures should be followed in their maintenance:

- o LAUNDER THEM AS INFREQUENTLY AS POSSIBLE. WHEN YOU DO LAUNDER THEM, USE COLD WATER WITH WOOLITE.
- o Do not launder the garments in hot water or with harsh detergents.
- o Do not use Clorox or similar bleaches.
- o Minimize the dry cleaning cycles.
- o If dry cleaning is required, request special handling similar to that provided to double knit clothes.
- o PLEASE MAINTAIN STRICT RECORDS ON THE CLEANING OPERATIONS. AT THE CONCLUSION OF THE TESTS, BALLISTIC TESTS WILL BE PERFORMED AGAINST SELECTED GARMENTS.

Your critical assessment and constructive comments on these garments is requested. Your comments will help us provide the best possible protection to you and your fellow officers. Three basic forms are provided to assist you in evaluating the garments: 1) The first is an interview form to gather general information; 2) The second will permit you to evaluate the garment weekly and to keep a record of the garment's cleaning history; 3) The third requests data about the garment when you are in a "stress" or high activity situation.

Your evaluation of the garments is important. Your assessment will be used to modify these garments to make them as useful as possible to yourself and other law enforcement personnel.

If you have any problems with the protective garment or are assaulted with a gun while wearing the protective garment, your departmental point of contact is requested to call:

Robert Merkle or Lou King
The Aerospace Corporation
El Segundo, California
Telephone: (213) 648-5000

I have read this statement and understand that the garment issued to me is a prototype garment in the developmental stage only. As consideration for my participation in the body armor wearability evaluation program and the issuance of the garment to me, I voluntarily assume the risk of any injury sustained by me while I am wearing such garment, and agree that neither the Law Enforcement Assistance Administration nor The Aerospace Corporation shall have any liability for gunshot or other injuries sustained while I am wearing the garment.

______________________________ ______________________
Participating Officer Date

INTERVIEW QUESTIONNAIRE

1. Name ____________________
2. Badge Number ____________
3. * Precinct ______________
4. (2-4) Test I. D. Number ____________
5. (5-8) Garment I. D. Number ________
6. (9-13) Date Garment Issued ________ Mo/Da/Yr
7. (14-18) Date Garment Returned ________ Mo/Da/Yr
8. (19-23) Test Begun ________ Mo/Da/Yr
9. (24-28) Test Terminated ________ Mo/Da/Yr
10. (29-31) Height _____ Ft. _________ In.
11. (32-34) Weight ______________ Lbs.
12. (35-36) Waist ______________ In.
13. (37-38) Chest ______________ In.
14. (39-41) Coat Size ________ ________
15. (42) Sex M _________ F _________
16. (43) Race:
    - A ___ White
    - B ___ Black
    - C ___ Latin American
    - D ___ Other (Specify)
17. (44) Marital Status:
    - _______ Single
    - _______ Married
18. (45) Number of dependents not counting yourself:
    - A ___ 0
    - B ___ 1 - 2
    - C ___ 3 or more
19. (46) How were you selected to participate in this program?
    - A ___ Volunteered
    - B ___ Selected by higher authority
    - C ___ Other (Specify)
20. (47) Have you ever participated in other experimental programs like this?
    - A ___ No
    - B ___ Once
    - C ___ Twice
    - D ___ 3 or more times
21. (48) If yes, how would you characterize your experience in these experimental programs?
    - A ___ Good
    - B ___ Fair
    - C ___ Poor
22. (49) If you answered poor, please explain.

    ____
    ____
    ____
    ____
    ____

*Data Processing Purposes

Form W 1

*

23. (50) How would you classify the precinct to which you are assigned?

A _______ Residential - Single Family
B _______ Residential Apartments
C _______ Commercial
D _______ Industrial
E _______ Other (Specify)

24. (51) What is the predominant Racial/Ethnic composition of your precinct?

A _______ White
B _______ Black
C _______ Latin-American
D _______ Other (Specify)

25. (52) How would you characterize the level of crime in your precinct?

A _______ Very high
B _______ High
C _______ About average
D _______ Low
E _______ Very low

26. (53) How long have you been a Police Officer?

A _______ less than 2 years
B _______ 2 to 5 years
C _______ 6 to 10 years
D _______ 11 to 15 years
E _______ more than 15 years

27. (54) What is your present rank?

A _______ Patrolman
B _______ Detective
C _______ Sgt. or Field Supervisor
D _______ Above Sgt.
E _______ Other (Specify)

28. (55) How often do you feel threatened while on duty?

A _______ very often
B _______ often
C _______ occasionally
D _______ seldom
E _______ never

Approximately how many times have you been assaulted in the line of duty?

	Never (A)	1 time (B)	2 times (C)	3 times (D)	More than 3 times (E)
29. (56) Handguns	____	____	____	____	____
30. (57) Shotguns and rifles	____	____	____	____	____
31. (58) Other dangerous weapon	____	____	____	____	____
32. (59) Hands, arms, fists, etc.	____	____	____	____	____

33. (60) Have any of these assults resulted in hospitalization?

A _______ none
B _______ outpatient
C _______ less than 1 week
D _______ more than 1 week

34. (61) Explain each incident with injury ______________________
____
____
____

Form W 1 *Data Processing Purposes

Daily	Once a Week	Several Times A Week	Infrequently	Very Infrequently	Never	Don't Know		*	
(A)	(B)	(C)	(D)	(E)	(F)	(G)			
____	____	____	____	____	____	____	35.	(62)	How frequently have you worn body armor in the past?
____	____	____	____	____	____	____	36.	(63)	While on duty how frequently do you feel a need for some type of protective armor?

37. (64) Do you think wearing soft body armor would make you a more effective officer?

A _______ agree
B _______ disagree
C _______ don't know

38. (65) If soft body armor were made available to you personally, how much would you be willing to spend annually to acquire a coat?

A _______ would not buy
B _______ less than $50
C _______ $51 to $100
D _______ $101 to $150
E _______ $151 to $200
F _______ over $200
G _______ don't know

39. (66-71) In what order would you recommend that your police department acquire the following equipment? (1 - 6)

(66) _______ communication helmet
(67) _______ improved airborne policing
(68) _______ lightweight body armor
(69) _______ active metal - weapon detection system
(70) _______ concealed recording system
(71) _______ routine wear ballistic helmet

40. (72) How do you think effective and lightweight soft body armor might change the way in which you perform your duty as a police officer?

____
____
____
____

Form W 1

*Data Processing Purposes

POST TEST ADDENDUM

	*		
A1.	(2-4)	Test I. D. Number ________	

A2. (5) Choose the statement which best fits your feeling about the soft body armor you have been wearing.

A. ____ This garment is too much trouble to wear.

B. ____ This garment should be used only for special hazardous duty assignments.

C. ____ This garment should be worn by all patrol car officers.

D. ____ This garment should be part of the patrolman's regulation uniform.

		Agree Strongly (A)	Agree (B)	Neither (C)	Disagree (D)	Disagree Strongly (E)	In general, during the test period.
A3.	(6)	___	___	___	___	___	The body armor garment was comfortable
A4.	(7)	___	___	___	___	___	The garment was easy to put on and take off
A5.	(8)	___	___	___	___	___	The garment allowed free movement
A6.	(9)	___	___	___	___	___	The garment allowed normal maneuverability
A7.	(10)	___	___	___	___	___	The garment allowed access to weapon

A8. (11) If you disagreed or disagreed strongly, please explain:

____

____

____

A9. (12-19) Disadvantages of the garment include (check as many as applicable)

(12) ____ too hot

(13) ____ rides up

(14) ____ chafes

(15) ____ binds

(16) ____ heavy and cumbersome

(17) ____ confining

(18) ____ other ________________

(19) ____ none

A10. (20) Describe any improvements or corrections you think would be desirable for the garment you wore.

____

____

Form W4

*Data Processing Purposes

WEEKLY DATA FORM

*		
1.		Name ____________
2.	(2-4	I. D. Number ____________
3.	(5-9)	Date ___/___/___ Mo Day Yr
4.	(10)	Duty assignment since last report

A. ___ auto patrol
B. ___ cycle/scooter
C. ___ foot patrol
D. ___ traffic
E. ___ detective
F. ___ other (Specify)

5\. (11-13) Shift start time during period

___ A. M.
___ P. M.

6\. (14) How would you characterize the level of crime in your duty area during report period?

A. ___ very high
B. ___ high
C. ___ about average
D. ___ low
E. ___ very low

7\. (15) What amount of the time did you wear the garment during the report period?

A. ___ all the time
B. ___ all but a few hours
C. ___ about half the time
D. ___ a few hours
E. ___ did not wear at all

8\. (16) What were the reasons for not wearing the garment?

____
____
____
____

Form W 2

*

9\. (17) Number of times garment was laundered during reporting period.

____

10\. (18) Number of times garment was dry cleaned during reporting period.

____

11\. (19) Number of times garment was water soaked during reporting period. (except normal laundering)

____

12\. (20) If the garment was soaked in any liquid other than water please explain.

____
____
____
____

13\. (21-30) The garment evidenced wear in the following areas:

(21) ___ seams opening
(22) ___ fasteners working loose
(23) ___ buttons falling off
(24) ___ ballistic material bunching up
(25) ___ wear at crease locations
(26) ___ wear at material edges
(27) ___ velcro does not hold well
(28) ___ appearance deteriorating
(29) ___ other ____________
(30) ___ none

* Data Processing Purposes

Agree Strongly (A)	Agree (B)	Neither (C)	Disagree (D)	Disagree Strongly (E)		*	
___	___	___	___	___	14.	(31)	Garment was easy to put on and take off.
___	___	___	___	___	15.	(32)	Garment fits well
___	___	___	___	___	16.	(33)	Garment allowed free movement
___	___	___	___	___	17.	(34)	Garment allowed easy access to weapon
___	___	___	___	___	18.	(35)	Garment allowed normal maneuverability

19. (36) If you expressed disagreement with any of statements 14-18, please explain your feelings:____________________

____

____

(A)	(B)	(C)	(D)	(E)			
___	___	___	___	___	20.	(37)	The garment hindered my movements while <u>pursuing a suspect</u>.
___	___	___	___	___	21.	(38)	The garment hindered my efforts to <u>subdue an adversary</u>.
___	___	___	___	___	22.	(39)	The garment hindered <u>easy access to my weapon</u>.
___	___	___	___	___	23.	(40)	The garment interfered with my efforts during a <u>rescue operation</u>.

24. (41) If you expressed agreement with any of statements 20-23, please explain your feelings:____________________

____

____

____

(A)	(B)	(C)	(D)	(E)			
___	___	___	___	___	25.	(42)	There was no change in garment comfort during a shift.

26. (43) If you disagreed, please explain:____________________

____

____

____

____

Form W 2

*Data Processing Purposes

*

27\. (44-49) If you were to characterize any discomfort experienced in wearing the garment, it would be (1 or more).

(44) ______ too hot

(45) ______ rides up

(46) ______ chafes

(47) ______ binds

(48) ______ too heavy

(49) ______ too cumbersome

28\. (50) Please note any comments you feel are pertinent to your experience with the garment during this reporting period or any changes you would like to see made in the garment.

____

____

____

____

____

____

____

____

*Data Processing Purposes

Form W 2