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High Speed Testing as a Measure of the Resistance to Penetration of Needle-Punched Felts

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Synopsis

Needle-punched felt samples differing widely in ballistic performance have been subjected to four different types of high speed mechanical tests. These tests included penetration, tensile, compression, and instrumented dart-drop methods. The results from one of these high speed tests, the penetration test, can be consistently related to the ballistic resistance of the felts. This penetration test utilizes a compression cage equipped with a penetrant and is operated at test speeds about two decades lower than those realized ballistically. The other three tests are of only limited use in evaluating felts.

Introduction

Resistance to high speed penetration is of especial interest to military research establishments because of requirements for personnel and vehicle armor. There is a constant effort in materials research to upgrade the effectiveness of armor in reducing casualties in personnel or losses in vehicles by increasing the penetration resistance of materials. This research is not restricted to conventional metals, fabrics, and laminates now in use, but includes new and unusual plastics, ceramics, and nonwoven fabrics.

The ballistic properties of nonwoven felts, or batts, have been previously investigated by the Army and by the Navy. The Navy work, conducted under a contract with Mellon Institute, was concerned with the buoyant characteristics of battings for life jackets and life-rafts rather than with their strictly ballistic properties.[1] Nonetheless it has led to some interesting results from the ballistic aspect. Both this Navy work and the Army tests showed that at low areal densities the nonwovens possessed much higher ballistic resistance than nylon armor fabrics now used in personnel armor.

From inspection of the fired battings, Jaskowski of Mellon Institute attributed their excellent performance to a "balling up" of the missile with fibers, thus involving a larger energy-absorbing area. In addition, he developed empirical relations that indicated the effect of fiber types, fiber denier, fiber length, and fiber friction upon ballistic resistance. Acrylic fibers, low deniers, long fiber lengths, and moderate friction favored good ballistic resistance.

The Army research, conducted and sponsored by the U. S. Army Natick Laboratories, emphasized different characteristics because of material requirements demanded by the intended application in an armor vest. Only needle-punched felts were investigated because of the problems that excessive bulk would have given to the armor designer responsible for good articulation and wearability in what is really an item of clothing.

Once these felts proved promising many questions would arise such as: (*1*) which fiber type, fiber length and fiber denier has the greatest resistance to penetration by fragments? (*2*) why are felts so resistant to penetration? (*3*) how can a manufacturer know if he has a felt with good ballistic properties?

Since felt companies do not have ballistic ranges, it will be necessary to find an effective, nonballistic test method, for selecting promising felts.

The following study was initiated by the U. S. Army Natick Laboratories in order to develop a test method for the theoretical and experimental study of felts resistant to high-speed penetration.

Experimental Materials

The following experimental needle-punched felts were obtained from Felters Corporation, Millbury, Mass. and were prepared under the direction of Mr. Raymond Stevens, Director of Research at that company.

The first four felts, the FL series, were all carded in the same direction on the same carding machine and were all needled on the same needling

TABLE I
Felt Samples

Material	Fiber	Fiber denier, dpf[a]	Staple length, in.	Felt density, oz./in.^{3}	Areal density, oz./ft.^{2}
FL acrylic-1	100% acrylic-1	6	2	0.080	3.3
FL modacrylic	100% modacrylic	50% 3 50% 12	1$^1/_2$	0.078	3.2
FL polyethylene	100% polyethylene	4	1$^1/_2$	0.088	3.4
FL polypropylene	100% polypropylene	6	1	0.074	3.4
Nylon C-500-58 (0.60 in. thick)	100% nylon	6	3	0.073	6.3
Nylon C-500-58 (0.11 in. thick)	100% nylon	6	3	0.134	2.1
Nylon, commercial (0.50 in. thick)	100% nylon	—	—	0.087	6.3

[a] dpf means denier per filament, where denier is the weight in grams of 9000 meters of the fiber.

machine. An attempt was made to obtain the same batt thickness and nearly equivalent felt density. The only polyethylene staple fiber available was 4 dpf, while the modacrylic was mixed (50% 3 dpf and 50% 12 dpf) to approximate the 6 dpf characteristics of the other felts.

The next two felts are of practical and historical interest. The nylon C-500-58 showed promise ballistically but was rather thick for clothing fabrications. This felt was fabricated in a more compressed fashion (by steaming and pressing) so that 3 layers of the material would have the same areal density but less than 60% of the thickness of the original sample.

The last felt, a sample of a commercially available nylon material, was included for comparison. No information is available on its fiber denier and staple length.

Experimental Methods

The test methods used in this study and as described in the following paragraphs include the ballistic V_{50} test. However, the objective of this study was to develop a high-speed test which would simulate the type of penetration of the ballistic test but at speeds at least one or two decades lower. If the study was successful, commercially available high-speed testing equipment such as that described in a recent Chemical Week article could be used to characterize the ability of a felt to resist penetration.[2]

a. Ballistic V_{50} Test

The felt to be tested was mounted 12 ft. 7 in. from a .22 Hornet rifle. The test missile is a .22 caliber, T-37 (17 grain) fragment simulator fired at different velocities by varying the powder charge. This is continued until ten shots are obtained of which five penetrate completely and five do not. A complete penetration involves penetration not only of the material but also of a witness plate of 0.020 in. aluminum alloy 2024T3. The ten shots mentioned above must be within a velocity range of 125 ft./sec. The so-called V_{50} is obtained by averaging the ten velocities and is really an estimate of the missile velocity which will result in equal probabilities of protection and of penetration. Suitable instrumentation is needed (lumiline screens or printed circuits) to trigger the counter-chronographs and measure the time of flight over a fixed distance from which the velocity is calculated. The complete test procedure is given in "Ballistic Acceptance Test Method for Personnel Armor Material" dated 28 June 1961.[3]

b. Penetration Test

A special compression cage was designed and fabricated having a rod, 2 in. long with a tip shaped as a .22 caliber fragment simulating projectile attached to the top portion of the lower part of the cage. This device is shown mounted on the Plastechon 581 in Figure 1. The felt specimen to be tested ($1^3/_4$ in. × $1^3/_4$ in.) was mounted in the bottom portion of the upper part of the cage.

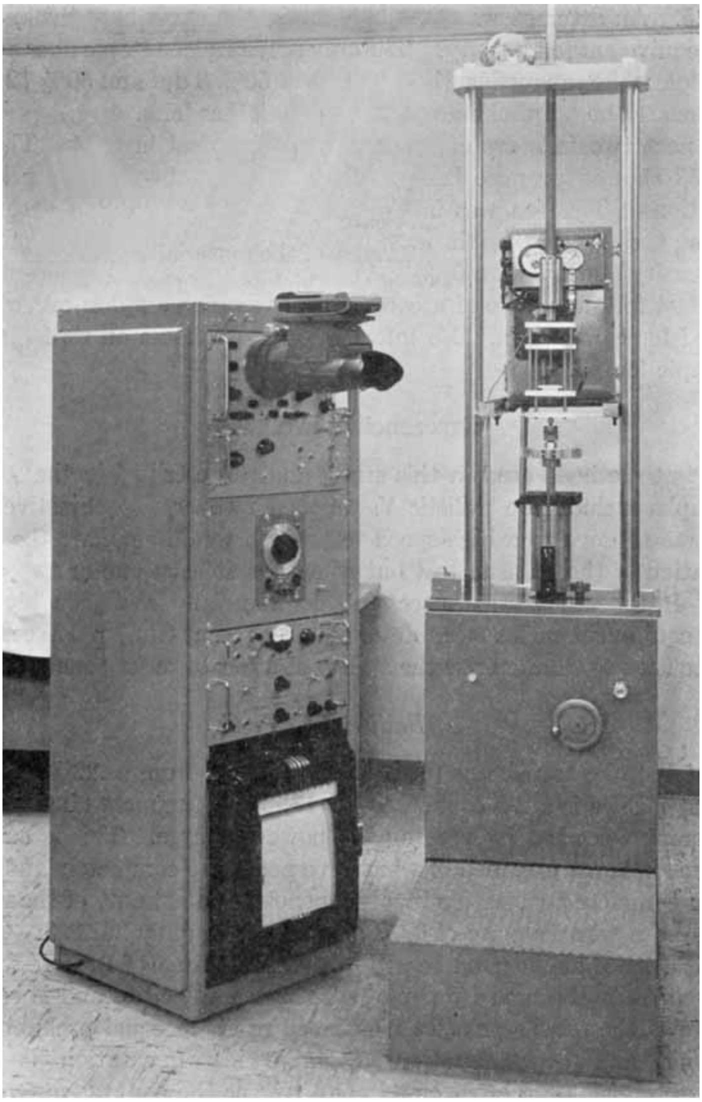


Fig. 1. Plastechon Model 581 with compression penetration cage.

Clamping of the specimen is accomplished by a flat steel plate having a 1 in. diameter hole in the center. Prior to the actual test, the projectile is positioned to touch the specimen (Fig. 2). The valve is set for maximum speed and the cylinder fired. Load is measured by a transducer of the unbonded strain-gage type. The output of the transducer is fed into the vertical axis of the oscilloscope. Displacement is measured by a linear potentiometer-type transducer, the signal from which is fed into the horizontal axis of the oscilloscope.

A Polaroid Land camera was used to obtain a permanent record of the

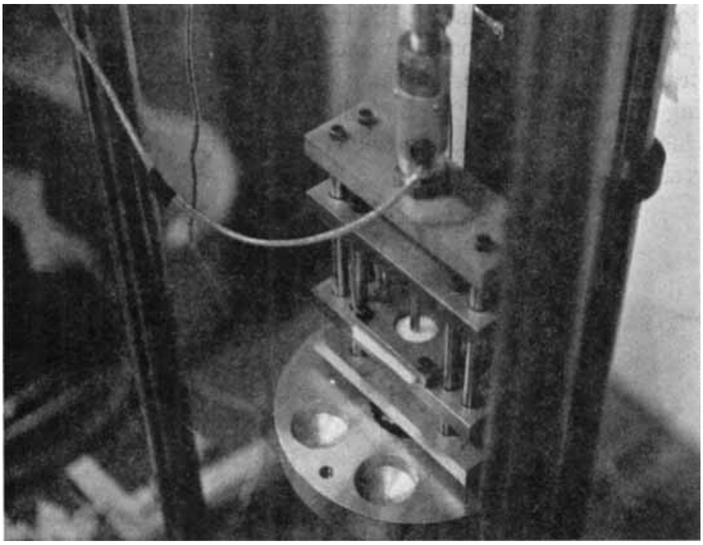
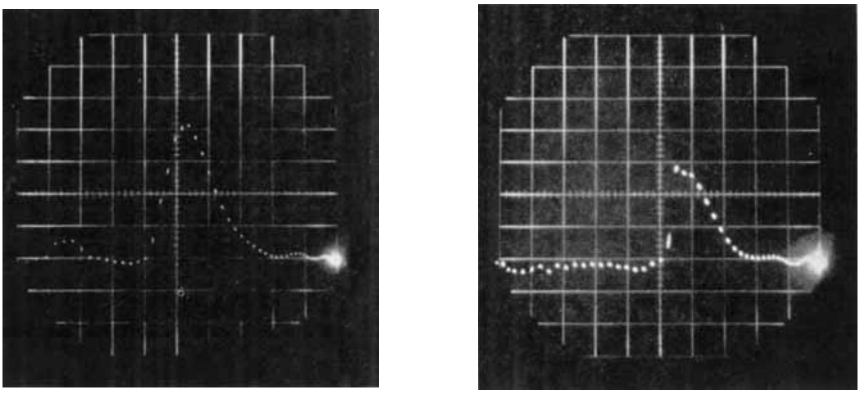


Fig. 2. Compression cage with projectile just touching specimen.



(*a*) (*b*)

Fig. 3. Typical load-deformation curves during penetration of felts: (*a*) FL polypropylene; (*b*) FL polyethylene (1 cm. vertical = 90 lb.; 1 cm. horizontal = 0.1 in.; time marker pulse = 5000 cycles/sec.).

load-deformation curve. The rate of loading averaged 10,000 in./min. over the major portion of the penetration time. Typical load-deformation curves for FL polypropylene and FL polyethylene are shown in Figure 3. Peak loads and inches of travel were recorded in this manner.

c. Tensile Test

Test strips, 6 in. long by 1 in. wide, were held by 1 in. serrated pressure grips and positioned, gauge length, in a bowed condition so as to provide 2 in. of slack. In this way, the piston was allowed to attain constant velocity before loading. Approximately $1^1/_2$ in. of travel was required at this valve setting to reach a truly constant velocity.

Again the Plastechon Tester was used as the highspeed device. Speeds of testing of just under 10,000 in./min. were attained. Load and elongation values were obtained as described previously. A typical tensile test curve is shown in Figure 4.

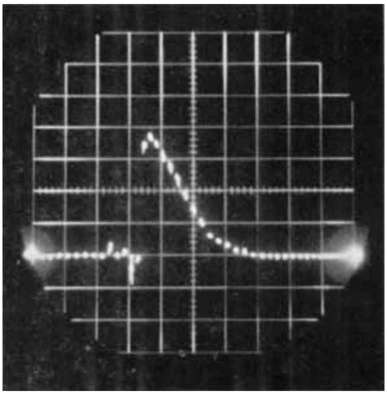
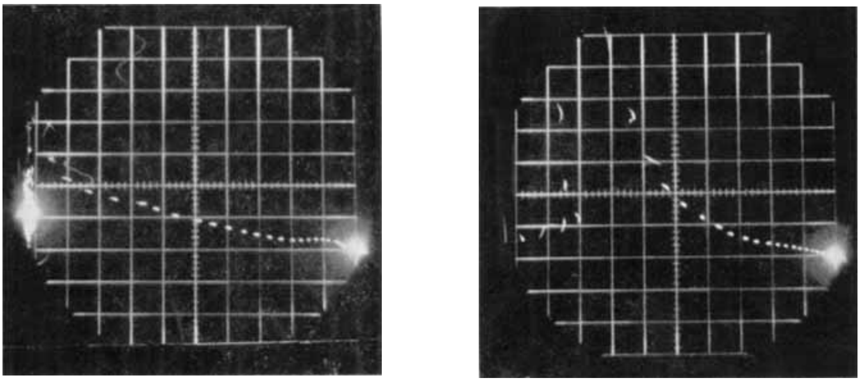


Fig. 4. Typical tensile test curve at 10,000 in./min. (FL polypropylene) (1 cm. vertical = 182 lb.; 1 cm. horizontal = 0.7 in.; time marker pulse = 1000 cycles/sec.).

d. Compression Test

Specimens (2 in. × 2 in.) were tested to 60% compression, accelerating from zero velocity to 3700 in./min. in a standard compression cage.[4] The compressive stress values at 36% compression were compared for the polypropylene and polyethylene felts. Typical load-compression curves are shown in Figure 5.



(*a*) (*b*)

Fig. 5. Typical load-compression curves: (*a*) polypropylene; (*b*) polyethylene; (1 cm. vertical = 90.9 lb.; 1 cm. horizontal = 0.0188 in.; time marker pulse = 5000 cycles/sec.).

e. Oscilloscope-Instrumented Dart-Drop Impact Test

The same .22 caliber tip used in the penetration test was attached to a shaft to form a dart for drop tests on the Plasti-Dart instrumented dart-drop tester.* This tester is shown in Figure 6. A dart is dropped from an electromagnet onto the specimen mounted on a rigid plate over a transducer of the unbonded strain-gauge type. The output of the transducer is amplified and fed into an oscilloscope. The curves obtained show the load transmitted through the test specimen on a fractional millisecond time scale and should thus reflect the energy-absorbing characteristics of the materials under test.

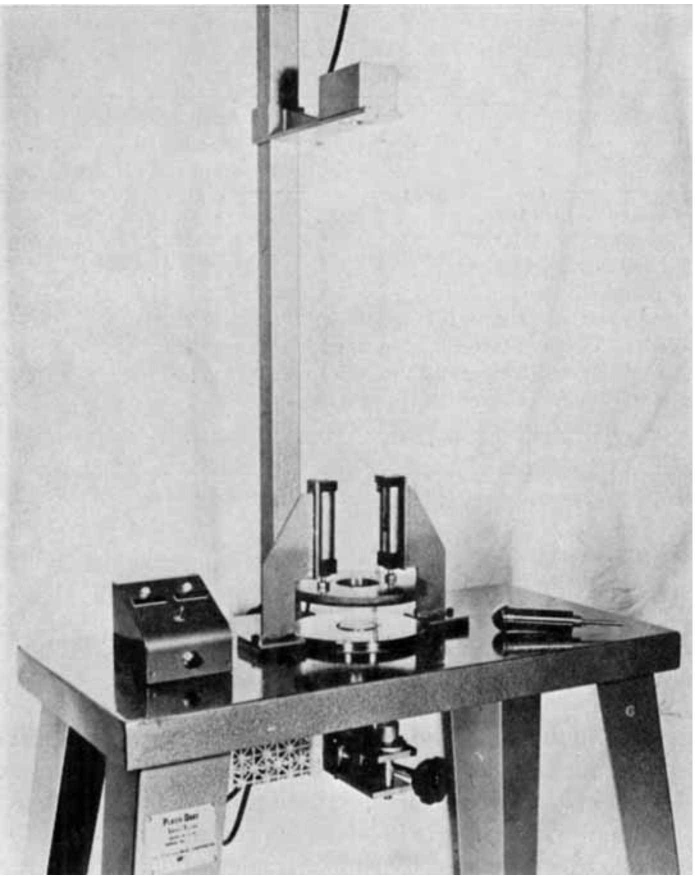


Fig. 6. Instrumented dart-drop tester.

Weights were added to the dart shaft to bring the total weight of the dart to one-third of a pound. The height of drop was 3 ft. which should yield a velocity of just under 10,000 in./min. on contact with the felt.

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* Manufactured by Plas-Tech Equipment Corp., Natick, Massachusetts.

Typical load-time curves were obtained from which both the peak load and the area under each curve were calculated.

Experimental Results

a. Ballistic V_{50} Test

The needle-punched felts were ballistically tested and the following results were obtained as shown in Table II.

TABLE II
Ballistic Results

Material	Areal density of tested sample, oz./ft.^{2}	Ballistic limit velocity,[a] ft./sec.
FL acrylic-1 (1 layer)	3.4	634
FL modacrylic (1 layer)	3.4	695
FL polyethylene (1 layer)	3.4	553
FL polypropylene (1 layer)	3.4	898
Nylon C-500-58 (1 layer 0.11 in. thick)	2.2	798
Nylon C-500-58 (2 layers 0.22 in. thick)	4.4	1050
Nylon C-500-58 (3 layers 0.33 in. thick)	6.6	1139
Nylon C-500-58 (1 layer 0.60 in. thick)	6.3	1070
Nylon, commercial felt (1 layer 0.50 in. thick)	6.3	914

[a] For 17-grain fragment simulator.

The FL felts were tested at a thickness of one layer to give the areal densities listed. The Nylon C-500-58 was tested in single layers of thin or thick felt and in multiples of thin 0.11-in.-thick layers.

b. Penetration Test

For the penetration test, the peak loads were taken as indicative of the relative resistance to penetration. The distance of travel (displacement) during the rise in load, when combined with the load value, gives a relative estimate of the work to rupture involved in penetration. Work to rupture in inch-pounds was estimated by simple triangulation. These results are shown in Table III.

c. Tensile Test

The results of the tensile test on the felt samples FL polypropylene, FL polyethylene and the single thickness of the 0.11-in. Nylon C-500-58 are given in Table IV.

The terms "lengthwise" and "across" refer to directions that are parallel to and at right angles to carding respectively. The felts were tested in both directions in some cases in order to determine the anisotropicity of the materials.

TABLE III
Penetration Results on Felt Samples

Material	Areal density,[a] oz./ft.^{2}	Peak load during penetration, lb.	Displacement during rise, in.	Work to rupture (by triangulation) in.-lb.
FL acrylic-1	3.4	214	0.23	24.5
FL modacrylic	3.4	189	0.29	27.6
FL polyethylene	3.4	218	0.19	19.7
FL polypropylene	3.5	398	0.29	57.6
Nylon C-500-58 (1 layer 0.11 in. thick)	2.1	207	0.29	30.0
Nylon C-500-58 (2 layers 0.22 in. thick)	4.3	434	0.33	71.5
Nylon C-500-58 (3 layers 0.33 in. thick)	6.5	666	0.37	124.0
Nylon C-500-58 (1 layer 0.60 in. thick)	6.3	552	0.29	80.0
Nylon, commercial (1 layer 0.50 in. thick)	6.3	345	0.31	53.3

[a] Average density of number of layers tested.

TABLE IV
Tensile Data Obtained on Felt Strips (1 in. × 6 in.) @ 10,000 in./min.

Material	Ultimate strength, lb.	Ultimate elongation, %	Work required to break, in.-lb.
FL polypropylene (lengthwise)	643	59	551
FL polyethylene (lengthwise)	343	55	315
Nylon C-500-58 (0.11 in.) (lengthwise)	205	45	189
FL polyethylene (across)	110	81	178
Nylon C-500-58 (0.11 in.) (across)	83	62	103

d. Compression Tests

Compression tests were conducted at a rate of loading accelerating from zero to approximately 3700 in./min. The two samples chosen for testing were the two extremes ballistically. The average values of compression stress obtained at 36% compression are shown in Table V.

TABLE V
Average Compression Data on Felt Materials at 36% Compression

Material	Load, lb.	Stress, psi
FL polyethylene	272	81
FL polypropylene	150	42

e. Dart-Drop Impact Test

Three members of the FL series of felts (polypropylene, polyethylene, and acrylic-1), in addition to 1, 2, and 3 layers of the 0.11-in. nylon felt C-500-58, were subjected to the dart-drop test. The average results expressed both as peak load and as an impulse function (the area under the curve in pound-seconds) are given in Table VI.

TABLE VI
Average Dart Drop Impact Results

Material	Peak load, lb.	Area under curve, lb.-sec.
FL polypropylene	577	0.132
FL polyethylene	509	0.096
FL acrylic-1	546	0.131
Nylon C-500-58 (1 layer 0.11 in. thick)	855	0.137
Nylon C-500-58 (2 layers 0.22 in. thick)	512	0.139
Nylon C-500-58 (3 layers 0.33 in. thick)	309	0.125

Discussion

The felts selected for this study were not prefectly comparable due to differences in areal density, felt density, and staple length. However, the felts represented a good selection as evidenced by the fairly wide spread in ballistic values obtained. Thus, at one extreme we have the FL polypropylene felt, which exhibited good resistance to penetration, and on the other extreme we have the rather poor resistance to ballistic penetration exhibited by the FL polyethylene felt. Secondly, we have the good ballistic resistance of the Nylon C-500-58 in multiple layers or as a single layer, contrasted with the poor ballistic resistance of the commercially available needle-punched nylon felt. These extremes were used as a basis for selecting highspeed mechanical tests that could screen out promising felts for ballistic applications or even furnish information concerning the mechanism of penetration.

Four tests were used of which the first, the highspeed penetration test, was the most similar to the ballistic test in shape of projectile, mode of operation and appearance of sample after test (Fig. 7). Because of these similarities, most of the emphasis was placed on the penetration test.

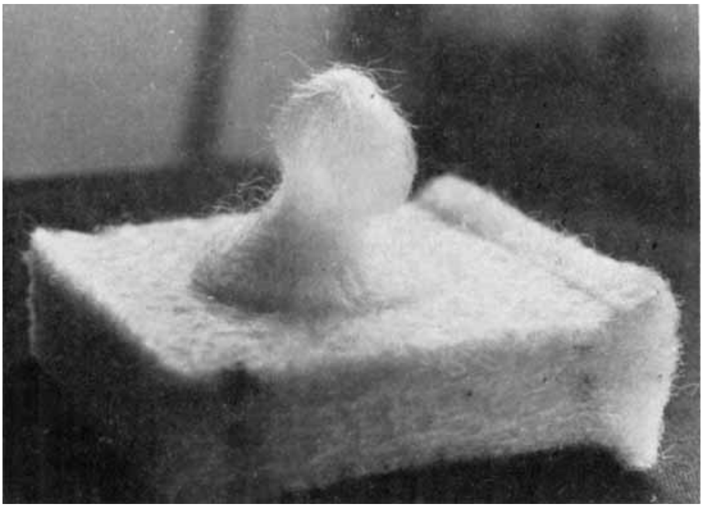

Fig. 7. Appearance of nylon felt sample C 500-58 (0.6 in. thick) after high speed penetration test.

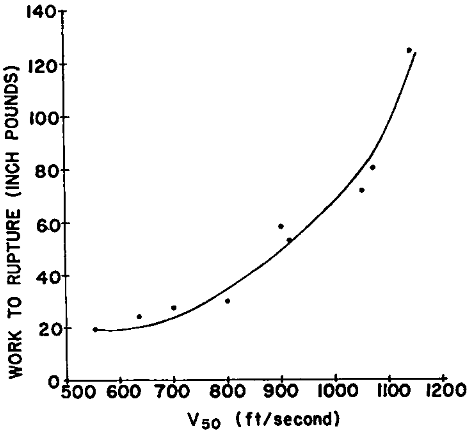

Fig. 8. Relationship between work-to-rupture by compression penetration tests and V_{50} by ballistic firing.

Comparison of the penetration results (Table III) with the ballistic results (Table II) shows that the felts that appeared most promising in the ballistic test also gave higher peak load and work-to-rupture values. Thus, for example, the FL polypropylene and the C-500-58 nylon felts (0.60 in. thick), which were good ballistically, exhibited peak load values in the penetration test of 398 and 552 lb., respectively, compared to the much lower peak values of 218 and 345 lb., respectively, exhibited by the ballistically poor FL polyethylene and commercially available nylon felts. Inspection of the data shows that a rough correlation exists between either the peak load or the work to rupture and the actual ballistic performance of the felt. In Figure 8, work to rupture has been plotted against the V_{50} ballistic value to illustrate this point. It appears from the curve that for felts of this type there may be an upper limit of penetration resistance (90 in.-lb.) beyond which additional resistance to penetration does not yield equivalent benefits in ballistic resistance. This curve of work to rupture against ballistic value, a hyperbola, is presently under examination using computer techniques.

The high speed tensile results appear to have limited use in selecting the best ballistic material (FL polypropylene) within a particular series. However, a danger exists when we compare felts of different types and thicknesses. The very thin nylon felt did not perform as well in tensile testing as it did ballistically. The results of the tensile testing also show the anisotropic nature of these felts, with tensile strengths about 2 to 3 times as great in the machine direction as in the cross direction.

The compression data in Table V show that a greater stress concentration at 36% compression (and at higher levels of compression) was obtained for FL polyethylene than for FL polypropylene. This might appear to represent a greater resistance to penetration in the case of polyethylene, contrary to the ballistic results. However, the important factor here is that the polyethylene "bottoms out" much more rapidly than the polypropylene. This feature should cause the polyethylene to reach its rupture stress more quickly and thus dissipate less of the energy of a missile than that characteristic of polypropylene. Considerably more work must be conducted on the compression behavior of felts before the usefulness of this test can be determined.

Since, in the dart-drop test, what is measured is the load transmitted, it was expected that the greater the resistance of the felt to ballistic penetration, the lower would be the load transmitted. This was not the case; in fact, FL polypropylene, with the highest resistance to penetration of the FL series, transmitted the greatest load. But, in the case of the 1, 2, and 3 layers of the C-500-58 nylon felt, the peak load changed in the correct direction. Here we were probably observing only a difference due to thickness and layering. This test does not appear promising. Any future work in this area should take account of the bounce imparted to the dart for a complete energy balance.

In conclusion, it can be stated that the dart-drop test in its present form shows no promise either for screening felts or for determining the mechanism of particle penetration of felts. The compression test may have some significance based upon the tendency of a felt material to "bottom out" but this factor may only be one of those influencing the ability of a felt to resist penetration. The simple tensile test has utility as a test that may measure some combination of fiber-fiber friction, entanglement, and fiber tenacity. The danger here is in comparing felts of varying types and thicknesses. The ballistic resistance of the thin C-500-58 nylon felt would be underestimated from this test. Only the high speed penetration tests appear to be suitable both for screening felts and for developing meaningful relationships between laboratory tests and resistance to ballistic penetration.

Not all the questions posed at the beginning of this paper can be answered at this time. From the work presented today, it appears that felts prepared from fiber types with relatively high work to rupture values are promising ballistically. This property, combined with the optimum fiber-fiber friction and fiber entanglement, probably predetermines the ballistic resistance of felt materials. Both the tensile test and the penetration test should measure these properties in the felt. However, it should be pointed out that Jaskowski at Mellon Institute has found that felts prepared from the moderate strength acrylic fibers are promising.

This paper only attempts to introduce the subject of the ballistic resistance of felts. A more sophisticated mathematical study of the factors involved in the ballistic penetration of felts will be sponsored by the U. S. Army Natick Laboratories this year.

The authors wish to thank Mr. Raymond Stevens of Felters Corporation, Millbury, Mass., for preparing the needle-punched felts. The ballistic tests were conducted by Mr. Odis Thompson of the Materials Research Branch of the U. S. Army Natick Laboratories. Many of the high speed tests on the Plastecon were conducted by Mr. Leonard Schreter of Plas-Tech Equipment Corporation, Natick, Mass., under Contract DA19-129-QM-1916. Development of the compression-case penetration adaptor for use with the Plastechon Tester was a joint effort by the authors and Mr. Melvin Silberberg of Plas-Tech Equipment Corporation.

References

1. Mellon Institute, *Ballistics Protective Buoyant Materials,* Department of the Navy Contract No. N140 (138) 68879B; *Quart. Repts.,* **1–4** (Nov. 1959–Jan. 1961).
2. Anon, *Chemical Week,* **89,** 85 (1961).
3. Military Standard *Ballistic Acceptance Test Method for Personnel Armor Material,* Standardization Division, Armed Forces Supply Center, Washington, D. C., June 1961.
4. Sandek, L., *Plastics Technol.,* **8,** 26 (1962).

Résumé

Des échantillons de feutre percés à l'aiguille et différant fortement du point de vue de performances balistiques, ont été soumis à quatre types différents de tests mécaniques à vitesse élevée. Ces tests comprennent la pénétration, la tension, la compression et les méthodes instrumentales de chute d'une pointe. Les résultats obtenus à partir de ces tests à vitesse élevée, le test de pénétration, peuvent être reliés à la résistance balistique de feutre. Ce test de pénétration utilise une cage de compression équipée d'un pénétrant et est utilisée à des vitesses d'essai inférieures d'environ deux décades à celles réalisées balistiquement. Les trois zutres tests sont d'un usage uniquement limité à l'évaluation des feutres.

Zusammenfassung

Nadel-gelochte Filzproben von sehr verschiedenem ballistischen Verhalten wurden vier verschiedenen ultraschnellen mechanischen Tests unterworfen. Es wurden Eindring-, Zug-, Kompressions- und Spitzenkörper-Fallmethoden verwendet. Die Ergebnisse eines dieser ultraschnellen Tests, des Eindringtests, zeigen Konsistenz mit der ballistischen Beständigkeit der Filze. Bei diesem Eindringtest wird ein mit einem Eindringkörper versehener Kompressionskäfig verwendet, und die Testgeschwindigkeiten liegen etwa zwei Grössenordnungen niedriger als bei ballistischen Versuchen. Die übrigen drei Tests sind bei der Bewertung von Filzen nur beschränkt brauchbar.