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RESEARCH ON A BASIC STUDY OF THE HIGH-SPEED PENETRATION DYNAMICS OF TEXTILE MATERIALS

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The report presents the experimental results and related discussions of a study on the factors controlling ballistic penetration of textile materials. In addition to a description of the experimental apparatus, the report presents data on ballistic and Instron penetration tests for a variety of polymeric films, natural and polymeric fibers in bonded, spun-bonded, woven, needled, and knitted textile fabrics. SEM studies on impacted fabrics are

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) included. Results indicate energy absorption capability depends on the ability of the fabric structure to propagate large strains as well as its rupture or penetration strength. The former is dependent on the degree of locking within the fabric for a given material; the latter was dependent on the tensile strength and modulus of the fabric with the greater energy absorption capability residing with the low modulus, flexible materials. Theoretical studies based upon the current experimental work are being addressed under a new grant and will be reported subsequently.

RESEARCH ON

A BASIC STUDY OF THE HIGH-SPEED PENETRATION DYNAMICS OF TEXTILE MATERIALS.

FINAL TECHNICAL REPORT

By

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M.A.I. Sultan, Research Fellow.

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SUMMARY

A variety of textile fabrics and other sheet materials have been tested for penetration by small high-speed missiles. Pellets were fired by an air-gun at a circular fabric desk. Methods of measuring the change of velocity on penetration or rebound were developed. The speed of the pellet was varied by passing through layers of polyethylene film. Impacted fabrics were examined by scanning electron microscopy.

The fabrics were further characterised by slow-speed penetration tests and by tensile tests on an Instron tester and by measurement of dynamic modulus.

Over a considerable range, the reduction in velocity was proportional to the target weight as the number of layers was increased. Paper was the least effective and woven nylon the most effective of the materials tested. The effects of various changes in test conditions are reported in detail and discussed.

The general conclusion is that the most effective materials are those with a high work of rupture and a low work factor (i.e.a load-elongation curve which shows stiffening at higher elongation).

CONTENTS

List of figures

Chapter 1.

INTRODUCTION

Textile fabrics have been used for many years as a form of flexible body armour in order to give protection against high-speed fragments. Practical trials have led to constructions which are reasonably effective, but, like most high-speed phenomena, the fundamentals of the behaviour of these systems are not well understood. Nor is it reasonable to assume that empirical development has led to optimum designs.

It is worth noting that, except for the elementary introduction to the subject and the simplest basic relations, studies of impact phenomena in other systems are not of great assistance. Because of the complexity of the problems, simplifying assumptions are always introduced - and the simplifications appropriate to one class of system are not appropriate to another class. Thus in metals, as brought out in Johnson's (1) recent book, the material properties are taken to be elastic-plastic and a dominant feature is the energy absorbed in bending at the "plastic hinge". But in most textile materials, the load-deformation curve is of a very different shape, as indicated in figure (1), and the sheet has little resistance to bending because of the freedom of relative movement of fine fibres: and when these features are less marked, as in bonded fibre fabrics, the impact resistance is poor.

The aim of the present work was to give some increase in understanding of the impact phenomena by a mixture of experimental work and simple theory. In the present state of the art, elaborate theory and complicated computer programming is not justified, since a complete solution of the mechanics of the problem is impossible, demanding as it would an analysis of the interaction of millions of elements: general qualitative understanding is needed before the right assumptions and models can be developed. A simple theoretical approach might however lead to semi-empirical relations of practical value.

The features which are important in the application are:

(a) the limiting conditions for non-penetration of the fabric by missiles.

(b) the energy absorbed from missiles which do penetrate.

(c) the magnitude of deformation.

For a given missile in particular fired at a given fabric, the relevant parameter is the initial velocity. Other features which will be involved are the mass, dimensions and shape of the missile; the angle of impact; the nature of any backing material.

In this report, the work carried out during the year is summarised and discussed. This work starts with the development of the previous ballistic apparatus to allow for velocity measurement and energy calculation. The experimental procedures for measuring the ballistic resistance of a small miscellaneous collection of materials have been given, and the results compared and discussed. The behaviour of materials during slow-speed tensile tests and penetration tests on the Instron tester have been investigated, and the relationship between the different fabric parameters have been deduced: this helps to characterise and give better understanding of the factors which influence ballistic penetration of textile materials.

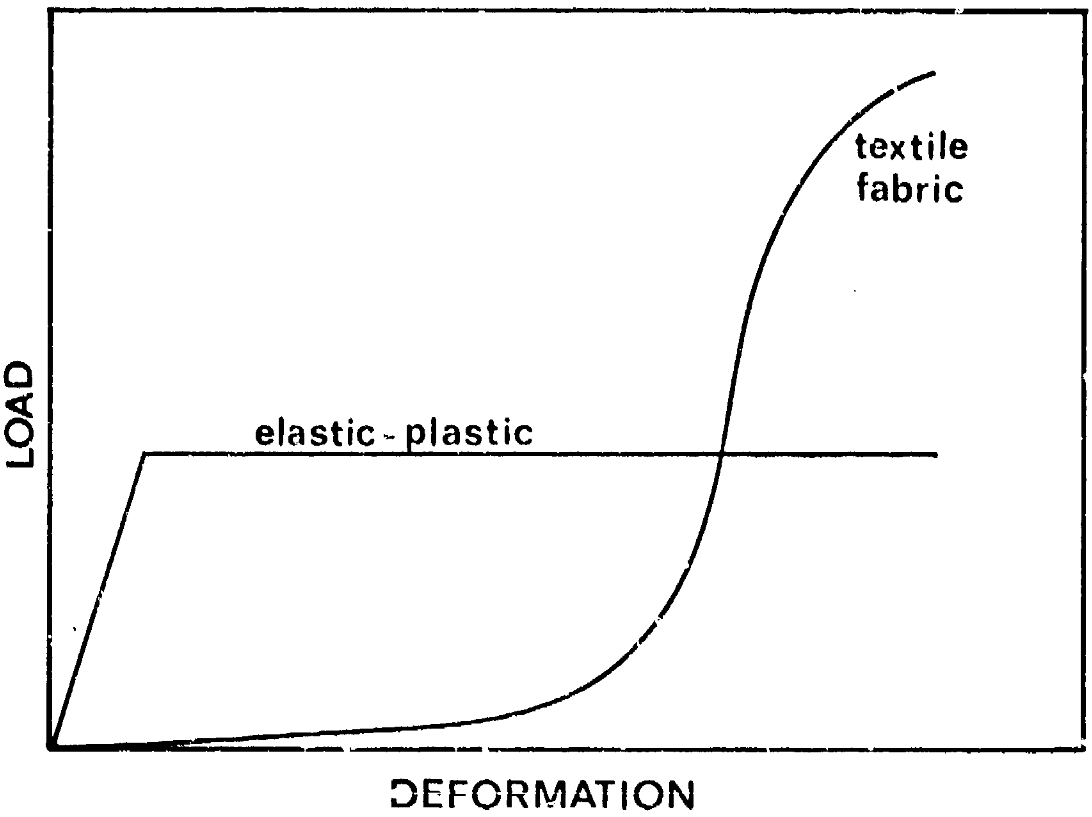


FIG. 1 Different shapes of load-deformation curves

The effect of varying the impact speed on the energy absorption of fabric has been examined and discussed for both woven and warp knitted fabrics, and the results have been discussed. The effect of reinforcing the impact point by strong fabrics has been tested, and the influence of loading the fabric around the impact point has been tried and investigated.

The fabric fracture due to impact has been studied with the S.E.M. to throw light on the mechanism of fabric failure due to ballistic penetration of different materials.

Chapter 2.

EXPERIMENTAL METHOD.

The ballistic penetration equipment.

The basic apparatus was used in the previous work(2) at UMIST, and it consisted, as illustrated in Fig. (2) of:

(a) A WEBLEY Mark 3 air rifle (0.22 in bore) with a firing velocity 146 m/sec., fixed on a supporting base which was bolted on a rigid table.

(b) A surrounding frame constructed from two aluminium side plates fixed to the table by two steel angles, and across them at the end a steel pellet-stopping plate with a thick (1½") foam pad stuck to it for pellet containment. The side plates had pairs of sliding guides, so that the specimen frame could be slid into place, in alignment with the rifle centre line. The specimen-clamping frame consisted of two square aluminium plates 8" x 8" x ¼" thick, with a 6" diameter hole in the centre. The square fabric specimen (8" x 8") could be clamped between the two plates which were pressed together by 8 bolts and nuts to allow perfect gripping, especially of woven fabrics which were not so easily held. A second specimen holder was used when needed, in order to hold material through which the pellet passed to give different initial velocities on the test specimen.

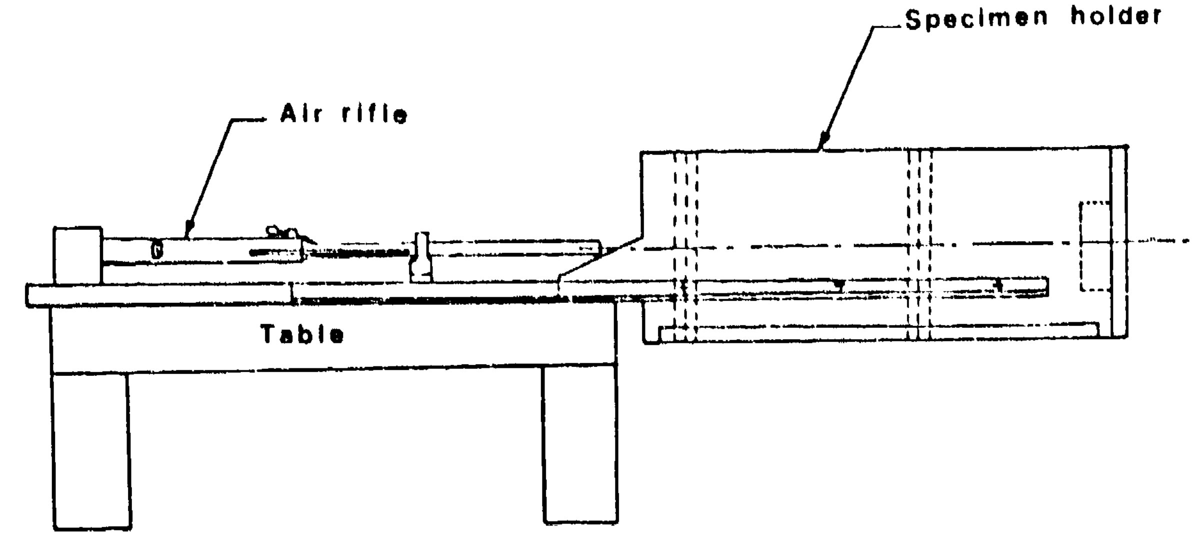
(c) The projectile used was a waisted lead pellet of weight 0.88 gm and calibre 0.22, trade mark MILBRO CALEDONIAN, and fig. (3) shows the shape of these pellets.

Velocity measurement.

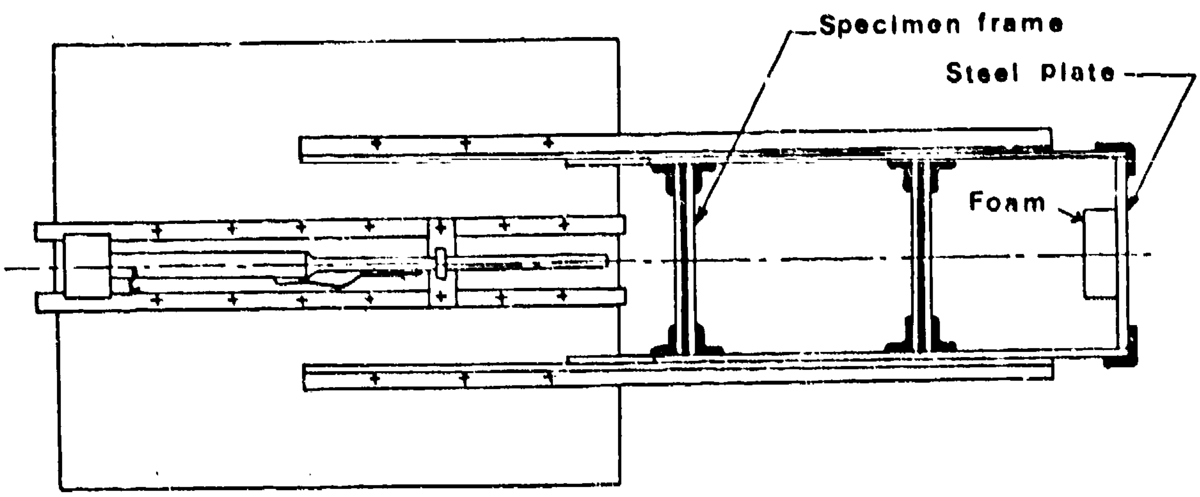
Two methods have been developed for measuring the pellet velocity before and after penetration, and these are described in the following.

(a) Photographic method.

The principle of this method is based on photographing the pellet with successive flashes before and after penetration. If the time between two successive flashes is known, the velocity of the pellet can be calculated by measuring the distance between the two successive photographed positions of the pellet. Fig. (4a) shows a diagrammatic sketch of the set-up of apparatus used in this method. The successive timed flashes were given by two Stroboscopes (max.freq.150,000 c/min) one flashing on the inward passage of the pellet, and the second flashing on the outward passage after penetration. The photography was carried out by a still camera using a fast film (Kodak royal, XPAN, rated at 1600 A.S.A.). The test was carried out in darkness, where the gun was fired during simultaneous flashing at 150,000 c/min (2500 Hz) from the two stroboscopes, and continuous opening of the camera shutter. The camera shutter was then closed immediately after firing. The suitable frequency of flashing was calculated to give at least two successive positions of the pellet within the illuminated range of the passage. Fig. (5) shows typical photographs with the pellet shown in successive positions, in both the cases of penetration and rebound. The scales were fitted on the apparatus near the inward and outward passages of the pellet, and appeared in the same picture, so that the distance between the two



Elev.



Plan

FIG.2 The Ballistic Penetration Equipment

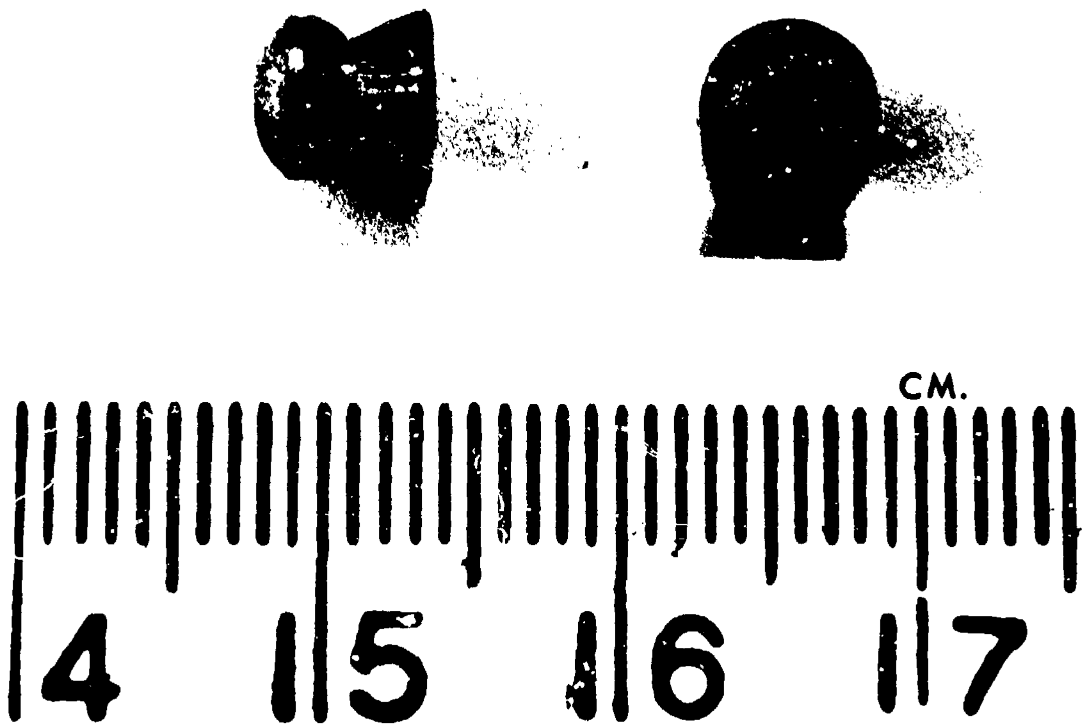
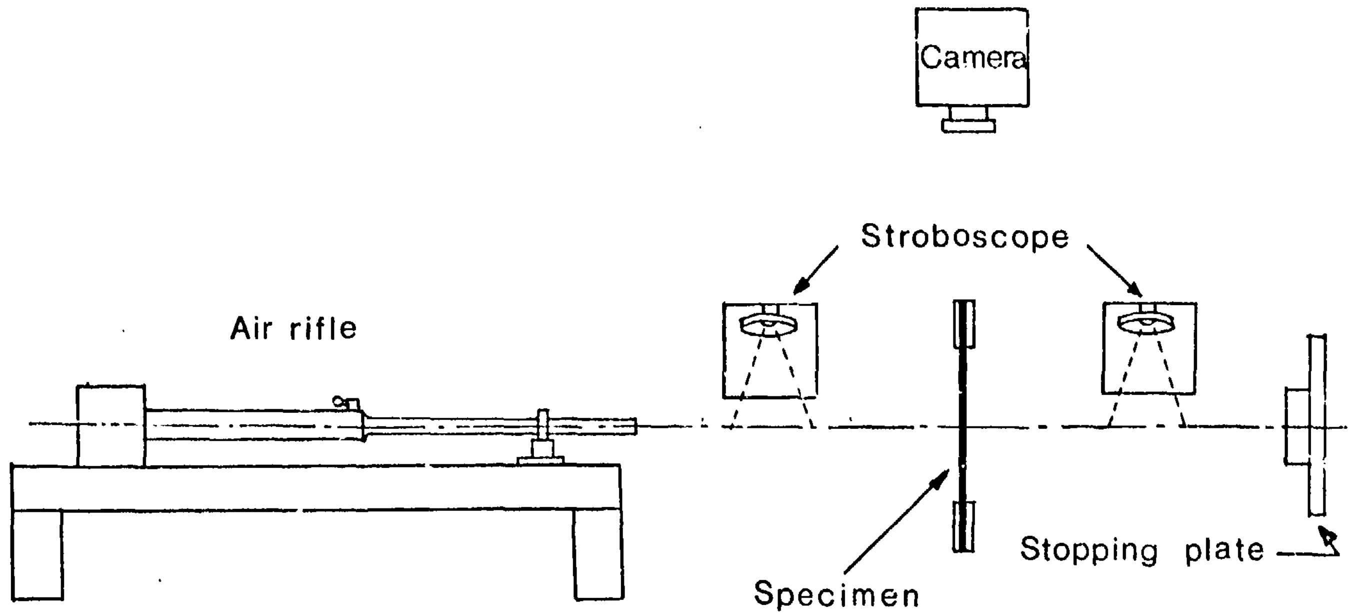
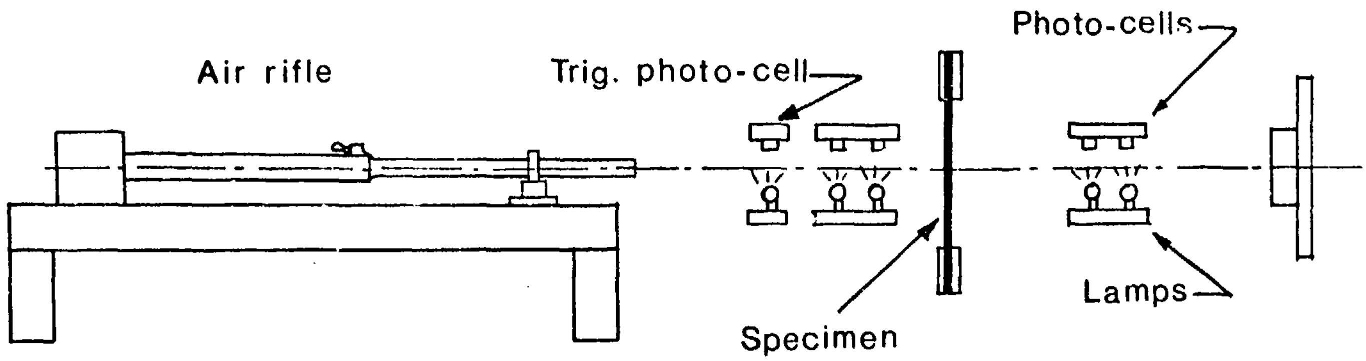


FIG. 3 SHAPE OF PELLET



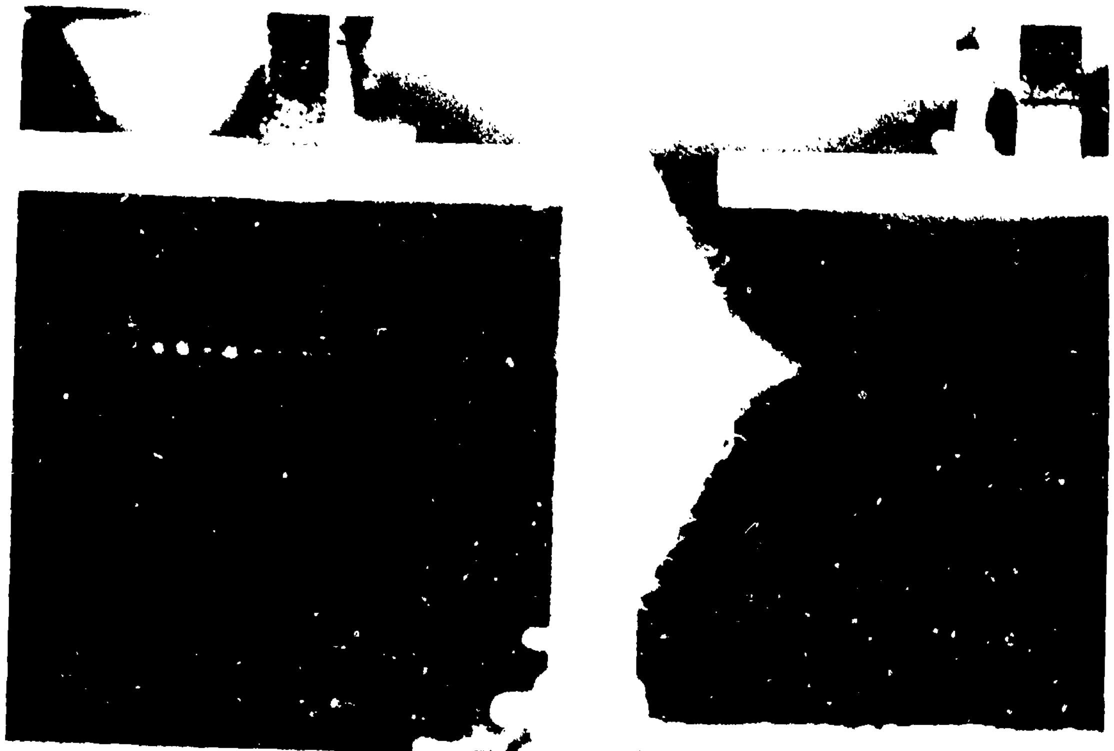
(a) Photographic method



(b) Photo-cell method

FIG.(4) Velocity-measuring devices for a travelling Pellet

a. Penetration



b. Bouncing

FIG. 5 PHOTOGRAPHING PELLET DURING IMPACT successive positions of the pellet on the inward and outward passages could be measured using a travelling microscope. The shape of the plastically deformed fabric and the maximum transverse deformation were also shown on the same picture.

Knowing the time between the two successive flashes to be 0.4 μ sec., and measuring the distance between the two successive photographed positions of the pellet, the velocity of the pellet can be calculated before and after penetration.

(b) Photo-cell method.

This method is based on the idea of causing the pellet to cross beams of light falling on photocells at 4 stations along its passage, two stations before penetration and two stations after penetration. A fifth station is used to trigger the recording. The signal caused by the passage of the pellet opposite to each photocell is recorded on an oscilloscope, so that the time between each pair of signals can be measured and the velocity of the pellet before and after penetration can be calculated. Fig. (4b) illustrates diagrammatically, the set-up of the apperatus using the photo-cell-stations technique, and fig. (6) shows the electronic circuit of the 5 photo-cells. The photo-cells are fitted at 5 positions close to the passage of the pellet, the first one triggering the oscilloscope, and the other four as recording stations. An ordinary oscilloscope (type D67) has been used at a setting of 0.2 or 0.5 ms/division (depending on the magnitude of the emerging velocity) so that the 4 blips recorded at the 4 stations could be enclosed in the screen. The set-up of the developed ballistic equipment is shown in fig. (7). The shutter of a still camera, set opposite to the oscilloscope screen, was left open during the firing in darkness, and the 4 successively appearing blips were registered on the film as illustrated in fig. (8). The time between each pair of successive blips was measured from the negative film using a travelling microscope reading 0.1 mm. Knowing the real distance between each pair of successive stations, the velocity of the pellet can be calculated both before and after penetration. The photo-cell method has been found easy, more practical, and more accurate than the photographic method, and so it has been preferred to be used as the main experimental method for measuring the pellet velocity in this study. The photographic method has been used occasionally to investigate the fabric deformation during penetration.

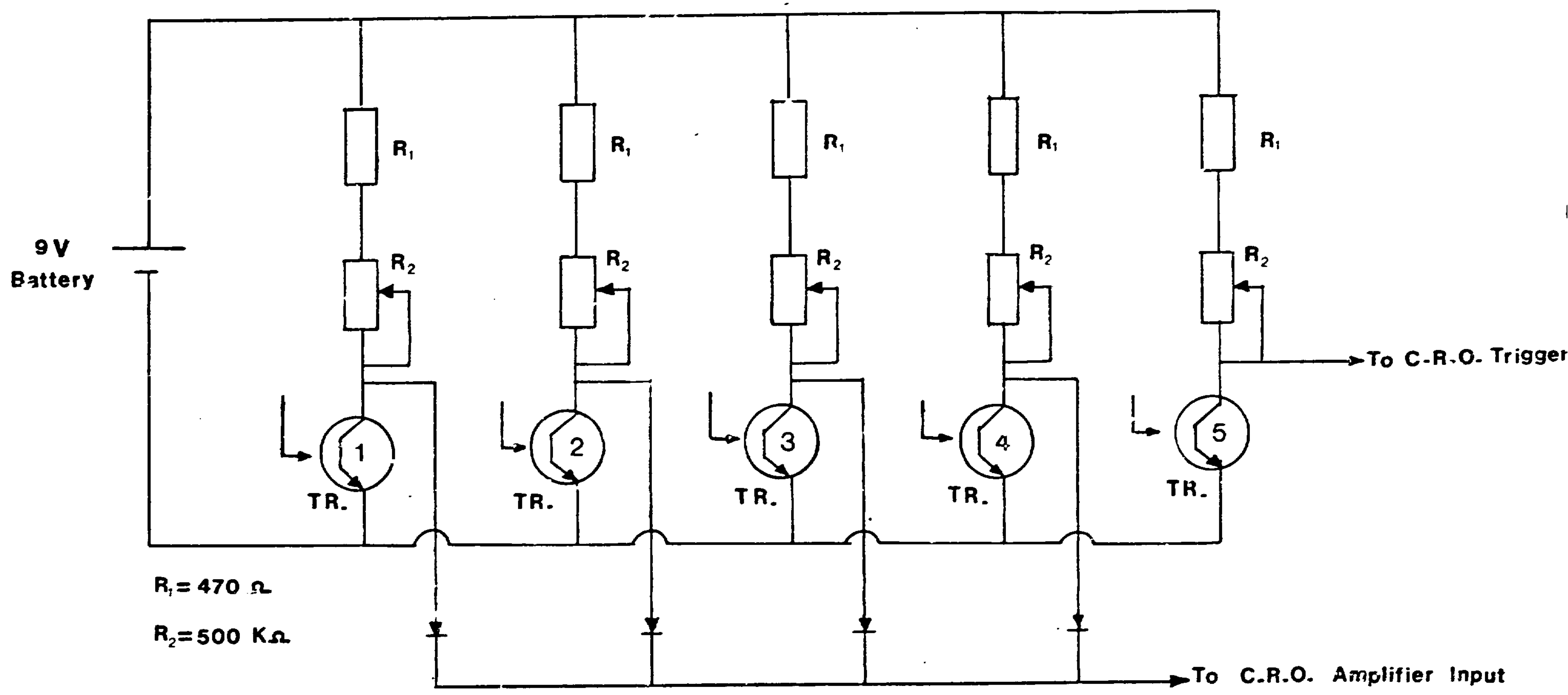


FIG. (6) Electronic Circuit Of The Photo-cell Arrangement

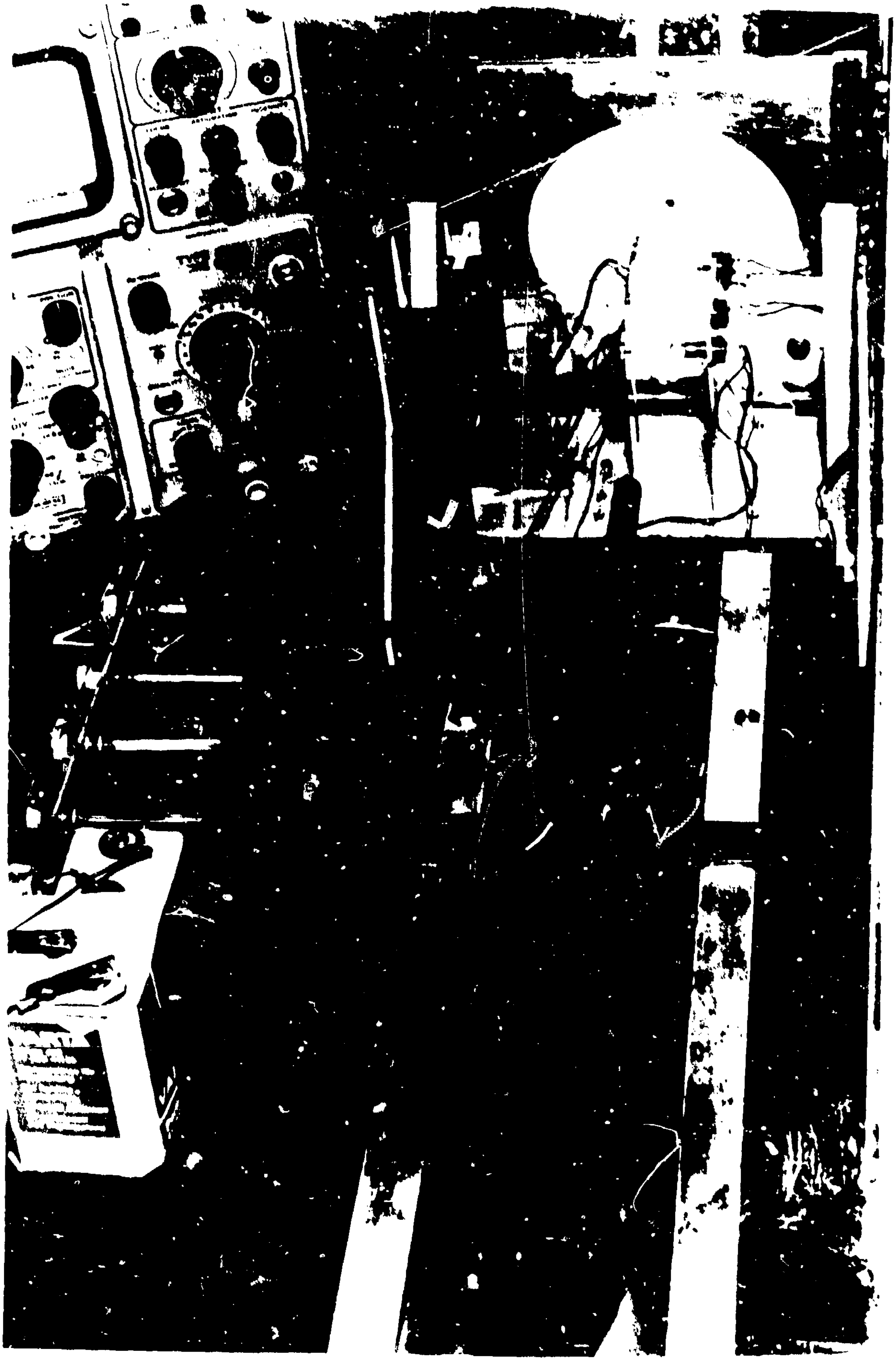
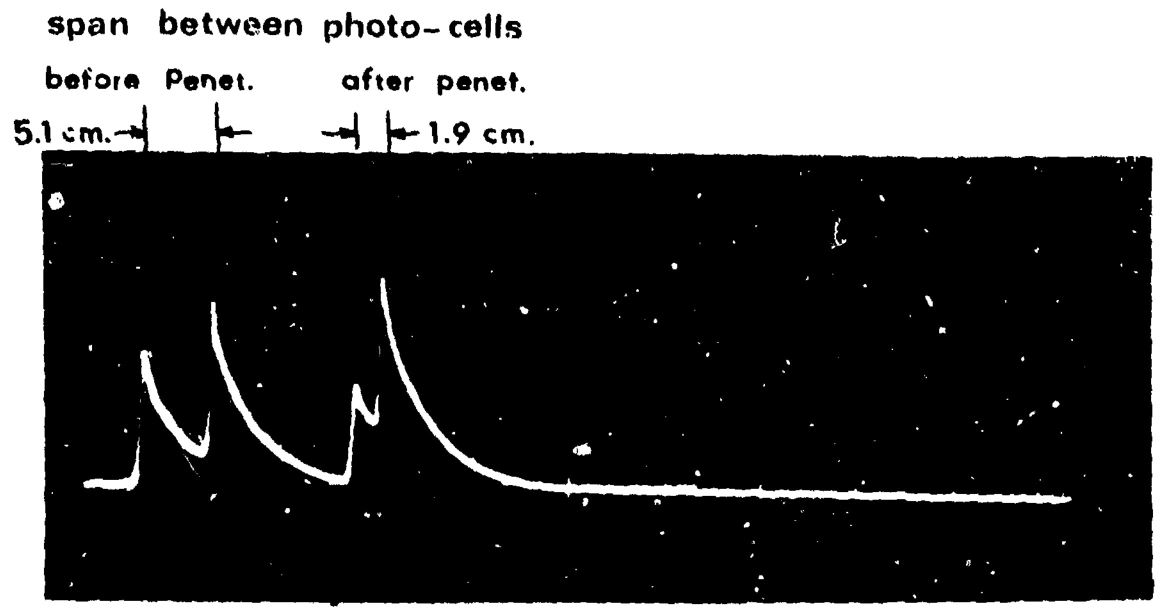
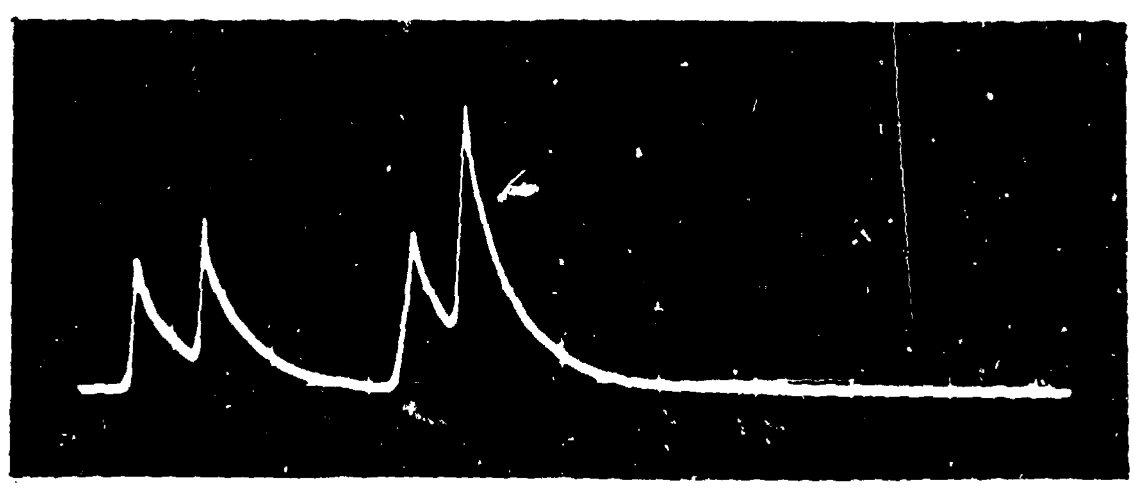


FIG. 7 SET_UP OF THE DEVELOPED BALLISTIC EQUIPMENT



a- TRACE WITHOUT MATERIAL



b- TRACE WITH MATERIAL

FIG. 8 4-blip trace recorded on the oscilloscope

Materials used.

The selection of materials used in the tests are given in the following table:

	Type of material	Weight g/m^2
1.	Paper (writing pad paper).	77
2.	Polyethylene film (a) heavy weight.	200
	(b) light weight.	50
3.	Woven steel fabric, 282 threads/in in both warp and weft, using steel wire threads 5.5tex	128
4.	Spun-bonded nonwoven fabric, polyester filaments. (By Du Pont).	106
5.	Bonded-fibre nonwoven (polyester fibre and acrylic binder).	185
6.	Spun-bonded nonwoven fabric, polypropylene filaments. (Typar by Du Pont)	110
7.	Bonded-fibre nonwoven (nylon fibre and acrilic binder).	157
8.	Woven cotton fabric (40 ends/in.break spun yarn 37 tex, and 40 picks/in,ring spun yarn 37 tex).	133
9.	Needle-felt from nylon fibre.	230
10.	Warp knitted nylon fabric, 22 wales/in,and 37 courses/in,using 100 den. multifilament yarn.	85
11.	Woven nylon fabric [illegible] ends/in.and 52 picks/in, both from 205 den.multifilament yarn.	116
12.	Kevlar woven fabric, Kevlar PRD 49, 17 ends/in and 17 picks/in, both 158 tex multifilament yarn. (Style 328 fabric by Du Pont).	220

Impact test procedure.

(a) Varying target weight at constant impact velocity.

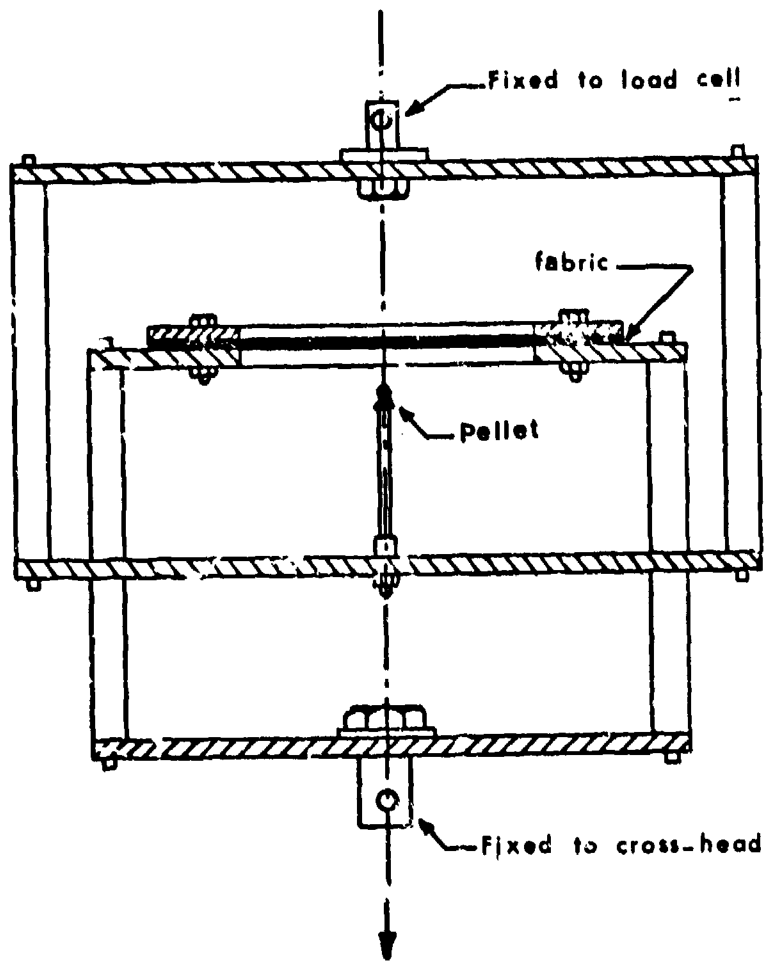
A series of samples with successively increasing numbers of layers was prepared from each material. The layers in one sample, being in contact with each other, form a whole target resisting the penetration by the pellet on the impact penetration equipment. The camera was set up opposite to the oscilloscope screen with its shutter open in darkness during the firing of the gun. The shutter was closed after firing, for the set up of the next test. The procedure for a series of tests can be carried out systematically without any practical trouble, or difficulty, or readjustment. By the end of a series of experiments, the whole negative film was taken from the camera, and developed, to obtain a series of 4-blip traces, each corresponding to one known sample, and indicating the velocity of pellet before and after penetration through this sample.

(b) Varying the impact velocity.

In order to vary the impact velocity of the pellet, sheets of polyethylene film were used to slow doen the pellet velocity. The second frame carrying the required number of sheets was used on the ballistic equipment as an initial target in the passage of the pellet at a position before the triggering station. The number of polyethylene layers required to give a definite velocity could be determined from the experimental relationship between the emerging velocity and the target weight for polyethylene. A series of constant-weight target specimens, each consisting of one layer, from the same material was tested at successively decreasing impact velocity, using a successively increasing number of polyethylene sheets in the slowing down target. The 4-blip trace for each test was registered and analysed in the same way as explained before. The polyethylene sheets seemed not to change the pellet orientation after slowing it down as was noticed from the symetry of the fracture in the impacted targets and the circular shape of the removed plugs.

Slow-speed penetration test procedure.

An attachment was designed to be fitted to the Instron tester for penetrating the material at a low speed (2 cm/min) as illustrated in fig. (9). The specimen in this test had the same dimensions and clamping conditions as in the ballistic tests. The clamping frame was attached to a framework mounted on the cross-head. The penetrating arm was attached to a framework suspended from the load-cell. The tip of the penetrating arm consisted of a pellet similar to that used in the impact tests. From the load-deformation curve recorded on the instrument, values indicating the penetration characteristics of the fabric were calculated. The problem of quantities and units involves difficulties, but for the present, the following quantities will be used: (a) Penetration stiffness, defined as the slope, at the point of origin, of the curve representing the relationship between the normalised load and the strain, where the normalised load is equal to the load divided by the mass/unit area of fabric (units are g.wt$(g/m^2)^{-1}$,) and the strain is equal to the transverse deformation divided by the specimen diameter (dimensionless). The units of the penetration stiffness are therefore g.wt$(g/m^2)^{-1}$.



STATIC PENETRATION ON INSTRON

FIG.(9)

(b) Penetration strength defined as the force causing rupture divided by the mass/unit area of the fabric, the units are g.wt$(g/m^2)^{-1}$.

(c) Maximum Bulge strain, defined as the maximum transverse deformation occurring in the fabric due to penetration, divided by the specimen diameter (dimensionless).

Instron tensile tests.

Tensile tests were carried out on the above materials in both the lengthwise and crosswise directions, using a strip specimen (20 x 2.5 cm), at a speed of extension 2 cm/min, and chart-to cross head speed ratio of 2.5, and load-cell CTM. From the recorded load-extension curve, the average value of the two tests in the lengthwise and crosswide directions was calculated for the modulus, the tenacity, the breaking extension and the energy (area under the stress-strain curve).

Dynamic modulus test:

The dynamic modulus was measured, for each of the above materials using the Morgan dymanic modulus tester (type PPM-5R). The basis of this method is the measurement of the velocity of propagation of a pulse with a frequency in the range from 3 to 10 kHz. The test was carried out for both the lengthwise and crosswise directions of the fabric, and the average of the two directions was taken to indicate the dynamic modulus of the fabric.

Pellet orientation after penetrating through polyethylene

The orientation of the pellet, after passing through the polyethylene target, did not change and the pellet hit the stopping plate with the same orientation with which it left the gun barrel. The evidence supporting this judgement was the shape of the accumulated smashed pellets at the surface of the stopping plate contained in the foam pad. After a number of impact tests, these smashed pellets were found superimposed concentrically and sticking over each other, forming a symetrical conical shape. This showed that all the pellets impacted the stopping plate at the same point and with the same orientation after passing through the polyethylene sheets.

Another observation which showed that no change in pellet orientation occurred due to passing through the slowing-down polyethylene sheets, was the circular or square shape of plugs removed from target impacted by pellets which had been slowed-down by polyethylene sheets. The Symetry in the shape of the plugs shows that the pellets hit the target with its initial orientation.

Chapter 3.

EXPERIMENTAL RESULTS.

High-speed impact tests.

Velocity reduction on penetration.

Fig. (10) shows the effect of increasing the target weight by increasing the number of layers of different materials on the emerging velocity of the pellet after penetration with an initial velocity of 146 m/sec. Values of the specific velocity reduction of the materials are compared in Table II. It appears that the emerging velocity decreases linearly with the increase of target weight over most of the range, but it tends to decrease at a higher rate near the stopping weight. The rate of decrease in the emerging velocity due to an increase in target weight differs according to the type of material. The slope of the linear relationship between the emerging velocity and the target weight - (the specific velocity reduction)- could then be taken as an indication to the effectiveness of the material for energy absorption in impact penetration. It can be noted that paper shows the least effectiveness in energy absorption (least slope), while the warp knitted nylon fabric shows the highest effectiveness. This difference in energy absorption could be related to the difference in the mechanical properties and the structure between the different materials, as will be discussed in the next chapter.

Effect of varying initial velocity.

Fig. (11) shows the effect of decreasing the impact velocity on the energy absorption of the target for both woven and warp knitted nylon fabrics. The decrease in the impact velocity tends to decrease the energy absorption of the target, but when the limiting velocity of the target (velocity just to penetrate the target and stop) is approached, the energy absorption tends to increase. This increase in energy absorption near the limiting velocity is more noticeable in the case of the woven fabric than in the knitted fabric. Comparing the woven fabric with the knitted fabric in the previous figure, it can be noticed that the target with the higher energy absorption (the woven fabric) shows a higher limiting velocity than the target with the lower energy absorption (the knitted fabric). The limiting velocity will therefore depend on both the weight and the effectiveness of energy absorption of the material.

Limiting velocity for penetration.

The initial velocities below which the pellet failed to penetrate the target were as follows: **Table I**

Material	Limiting velocity
(1) Knitted nylon fabric (85g/m^2)	85 m/s
(2) Woven nylon fabric (116g/m^2)	105 m/s
(3) Woven Kevlar (Style 328 fabric 220g/m^2	> 146 m/s
(4) 20 layer target of polyethylene 200g/m^2	146 m/s
Knitted nylon (85g/m^2) reinforced at the impact point by a square of needle nylon felt (230 g/m^2) 2.5x 2.5cm stitched along the circumference of the square.	146 m/s

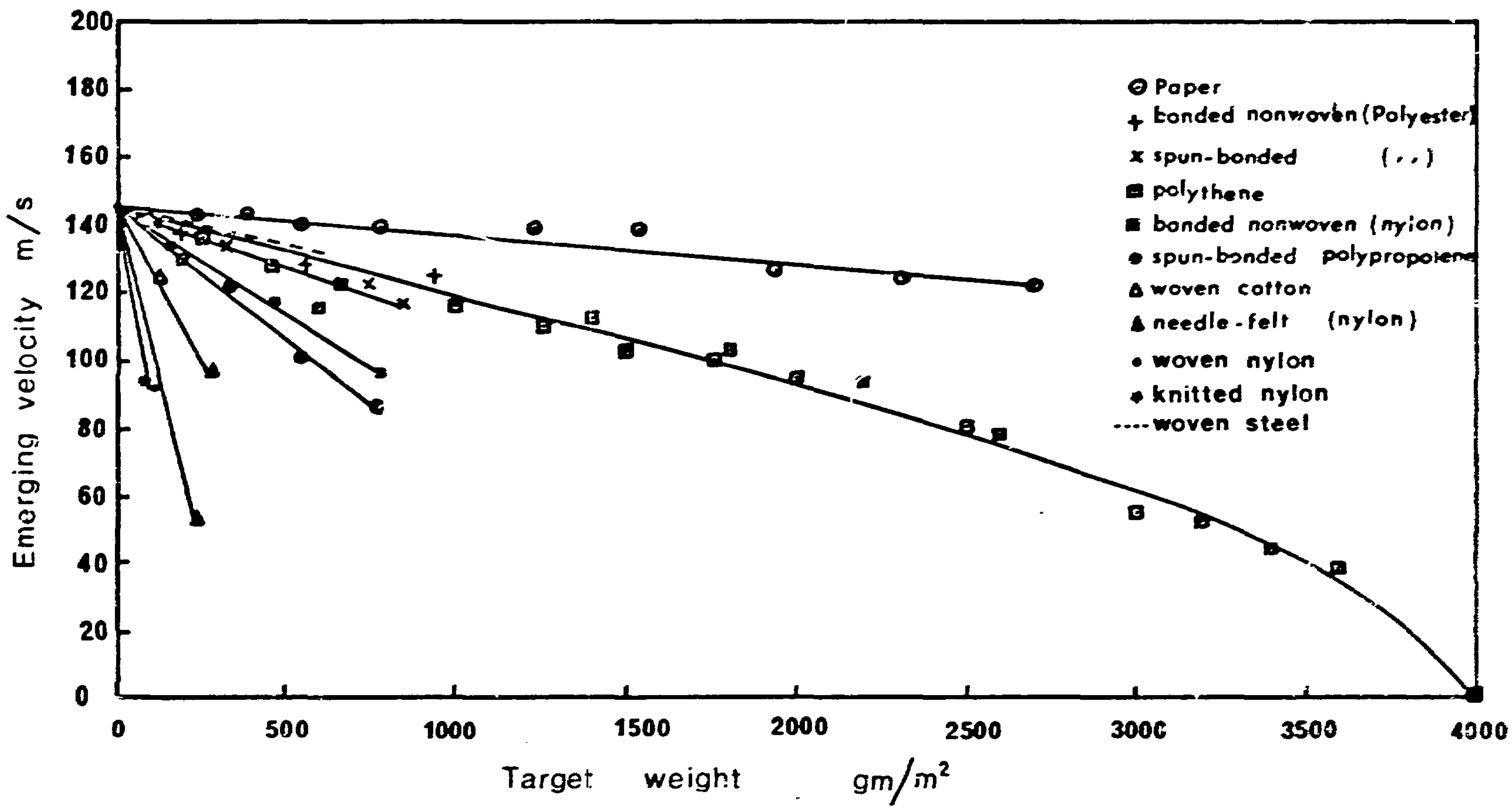


FIG. (10) Reduction in pellet velocity due to penetration

Table II

Specific velocity reductions at different number of layers.

Type of Material	Specific Velocity reduction $m^{-1} (g/m^2)^{-1}$				
	Number of layers				
	1	5	10	20	30
1. Paper 77 g/m^2	.01	.0052	.0078	.0052	.0091
2. Polyethylene 50 g/m^2	.04	.036	.04	.03	.029
3. Polyethylene 200 g/m^2	.023	.026	.023	.037	-
4. Woven steel 128 g/m^2	.031	-	-	-	-
5. Spun-bonded polyester 106 g/m^2	.038	.036	-	-	-
6. Bonded-fibre polyester 185 g/m^2	.043	.023	-	-	-
7. Spun-bonded polypropylene 110 g/m^2	[illegible]	.08	-	-	-
8. Bonded-fibre nylon 157 g/m^2	.076	.064	-	-	-
9. Woven Cotton 133 g/m^2	0.165	-	-	-	-
10. Needle-felt nylon 230 g/m^2	0.4	-	-	-	-
11. Warp knitted nylon 85 g/m^2	0.56	-	-	-	-
12. Woven nylon 116 g/m^2	0.578	-	-	-	-

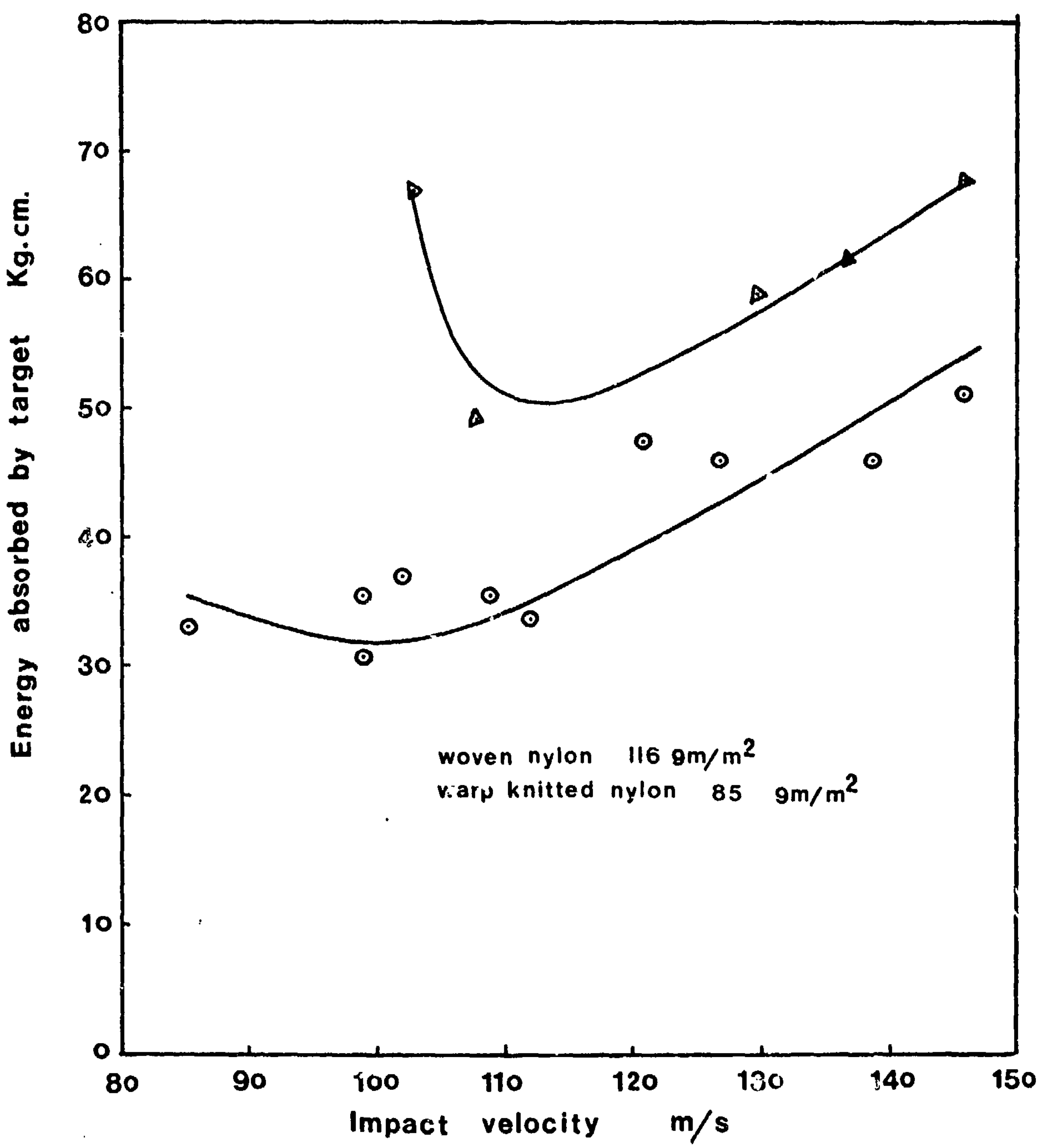


FIG. 11 Effect of initial velocity on energy absorption

Experiments on modified targets

(a) Targets reinforced at the impact point:

When the target is reinforced at the impact point by squares of needle felt, the energy absorption of the target increases and its limiting velocity increases accordingly, as illustrated in table III.

Table III Reinforcement of impact point.

Method of reinforcement fixation.	Effect on penetration resistance
1. Sticking with twin-stick at the four corners of the square.	No significant gain in the penetration resistance of the reinforced target.
2. Stitching at the centre of the square.	No significant gain in the penetration resistance of the reinforced target.
3. Stitching along the circumference of the square.	Considerable gain in penetration resistance, stopping the pellet (V50 of the reinforced target-146 m/sec Compared to V50 of 85.5 m/sec. for the fabric without reinforcement).
4. Stitching along the diagonals of the square	Stopping and bouncing of pellet, (V50 is higher than 146 m/sec, that is higher resistance to penetration than the previous case).

The improvement in the energy absorption of the reinforced target has been found to depend on both the penetration strength of the reinforcing material and the method of its fixation to the basic target. The diagonal stitching of the reinforcing squares to the knitted target gives more improvement in energy absorption than the circumferential stitching. If the reinforcing square is not strongly fixed to the target, it will not provide any substantial improvement in the energy absorption of the modified target.

(b) Targets loaded around the impact point:

The loading of the target (warp knitted nylon) around the impact point by sticking lead discs does not improve the energy absorption of the modified target, but on the contrary, the loading tends to decrease slightly the energy absorption of the target, as can be seen from table IV.

Table IV Fabric Loading and penetration strength.

Percentage increase in target weight. %	Energy absorbed by target. kg cm
0	51
95.5	48
191	45.3

This test shows that the effect of the kinetic energy of the target is not important as compared to its deformation energy.

Nature of deformation.

The observed form of deformation of the target during and after penetration has been found to depend on the properties and the structure of the target material. The following cases have been observed:

(a) Stiff fabrics:

The stiff fabrics with a random fibrous structure such as paper, bonded-fibre nonwovens, and spun-bonded nonwovens showed a very limited elastic deformation throughout most of the target, with the exception of the impact zone which showed large plastic deformation. After penetration, the target showed no sign of any dimensional change or any permanent deformation, except at the impact zone where the plastic deformation causing the fracture took place. The permanent deformation at the impact zone noticeable to an extent depending on the impact velocity and the plasticity of the target material. At lower impact velocities, and higher plasticity (such as polyethylene) the permanent deformation was noticeable, while at higher impact velocities and lower plasticity, (such as bonded-fibre nonwovens) no plastic deformation was noticed at the impact zone as can be seen from fig. (12a).

(b) Needle felt:

The needle felt target showed substantial plastic deformation throughout the whole target, reaching its maximum value at the impact zone, and decreasing gradually towards the target boundaries as can be seen from fig. (12,b). The excessive plastic deformation associated with the deformation of this target caused a considerable change in the dimensions and the shape of the circular target which was deformed into a permanent conical shape.

Woven nylon fabric.

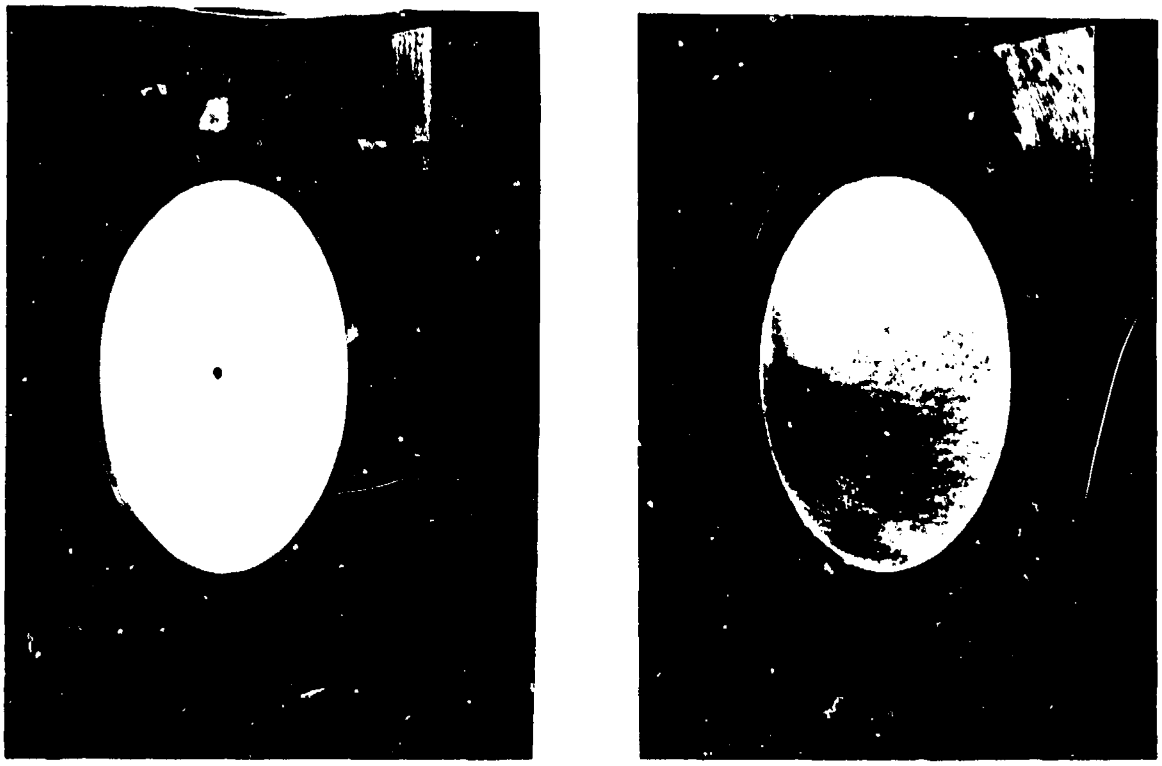
The woven nylon fabric was deformed with large elastic strains extending from the impact point to the target boundaries until the threads at the impact zones were plastically deformed and penetration occurred. After penetration, the target showed no permanent deformation except at the impact point where the threads orthogonal at the impact zone, were fractured and slackened.

Knitted nylon fabric.

The deformation of the knitted fabric showed large strains throughout the target, and after penetration the fabric showed permanent deformation especially near the impact zone where the threads were fractured.

Woven steel fabric.

The fabric showed very limited elastic deformation throughout the target, but around the impact point, plastic deformation occured, leading to fracture of a plug of fabric across both the warp and the



a .Bonded.fibre nonwoven

b .Needle.felt

FIG.12 GENERAL VIEW OF PENETRATED FABRICS weft threads. The penetrated fabric showed some tearing across the warp and the weft threads around the impact point, but the rest of the target showed no sign of any permanent dimensional change.

Removal of plugs due to penetration

The ballistic penetration of the pellet through the target tended in general, to remove a plug of the material, which was carried away by the pellet. However, in some fabrics, the penetration occurred not due to the removal of a plug from the material, but due to the fracture of the fabric at the impact point, such as the cases of the woven nylon fabric, the knitted nylon fabric and the spun-bonded polypropylene fabric. In some cases, the plug was not completely removed, but it remained attached to the target at one side, such as the case of the needle nylon felt.

In the case of stiff fabrics with random fibrous structure, such as the bonded-fibre fabrics or paper the removed plugs were approximately circular. But in the case of the woven cotton fabric or the woven steel fabric, the removed plugs were square. This is clearly because the fracture occurs across lines depending on the structural anisotropy.

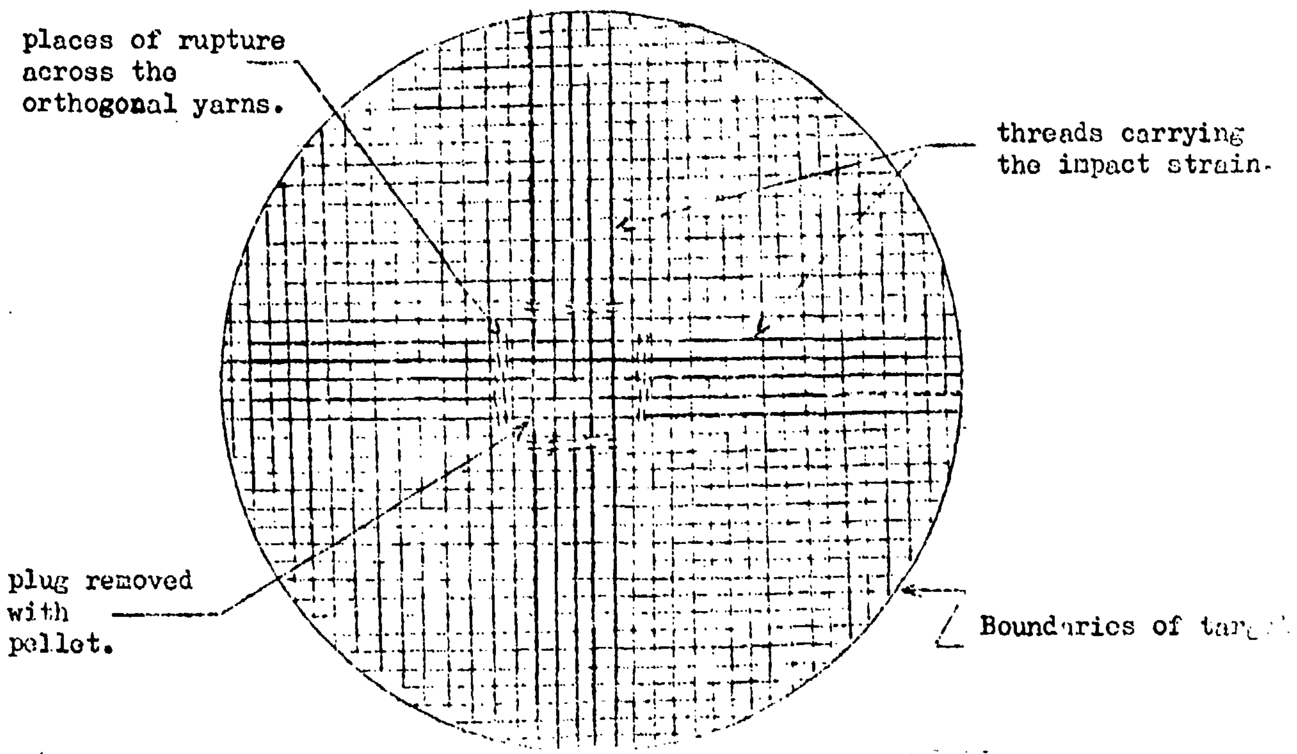
In the case of the materials whose tearing strength was very low, such as paper and the woven steel, the removal of the plug was associated with some tearing along directions perpendicular to the circumference of the penetration hole.

SEM studies of impacted materials

The impact zone was investigated by SEM for a number of penetrated and unpenetrated materials, and the remarks observed on each material are given in the following:

Penetrated woven cotton fabric

Fig. (13) shows the SEM photographs for both the impact zone in the fabric, and the plug carried away with the pellet. The impact zone shows that both warp threads and weft threads are ruptured. The square plug shows that the impact energy was mainly absorbed by a low number (about 5) of both warp and weft threads intersecting with the impact zone, as illustrated in the following diagram.



Impact Zone of penetrated woven cotton fabric.

Fig. (13) (impact velocity 146 m/sec)

a. - Fabric fracture at the impact zone, showing rupture of both warp and weft yarns.

b. - Fractured Cotton fibres at the impact zone.

c. - Shape of fractured ends of the cotton fibres in the fabric.

d. - Plug of fabric carried away with the pellet.

e. - Fractured ends of fibres in the plug.

f. - Fracture surface of fibre in the plug.

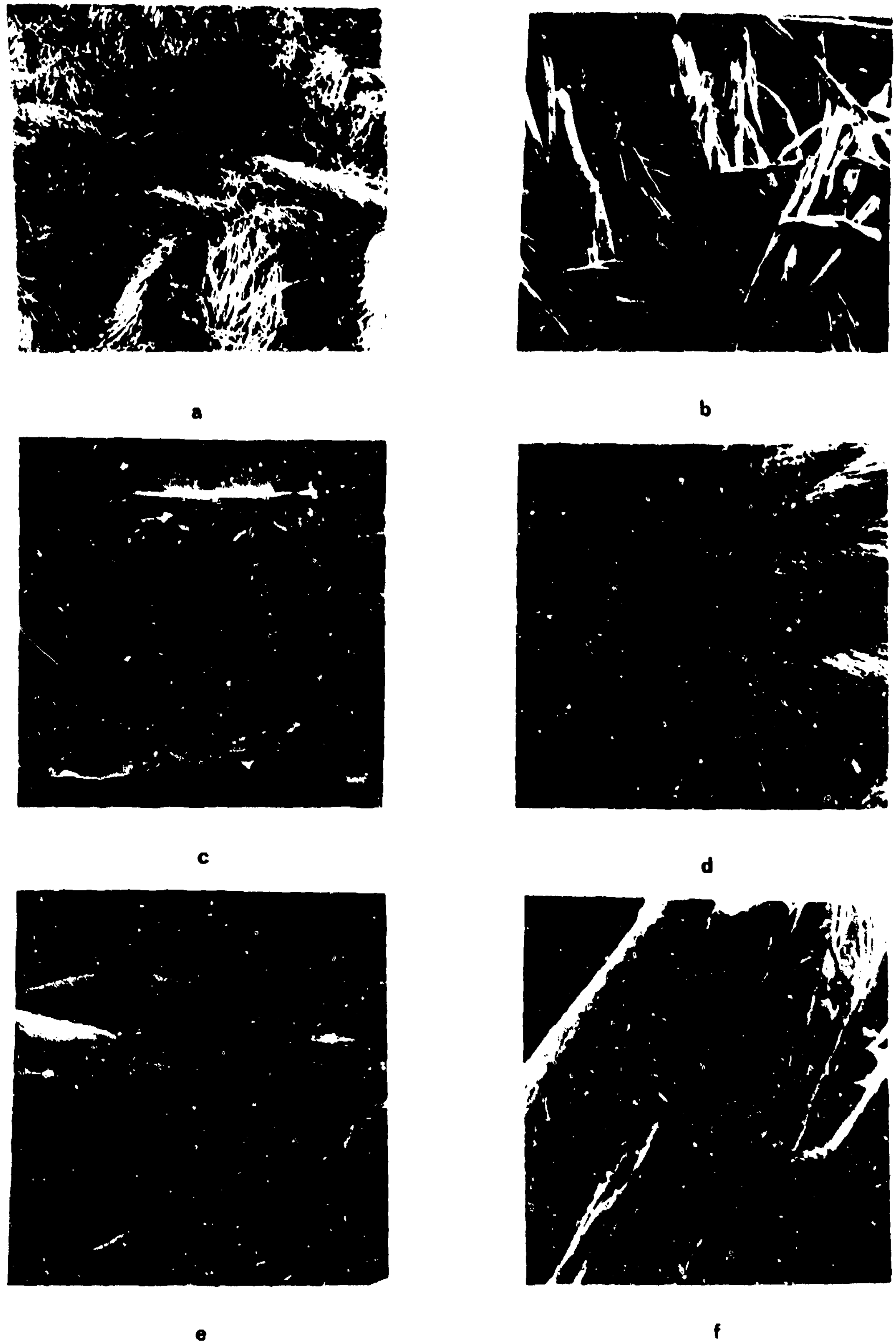


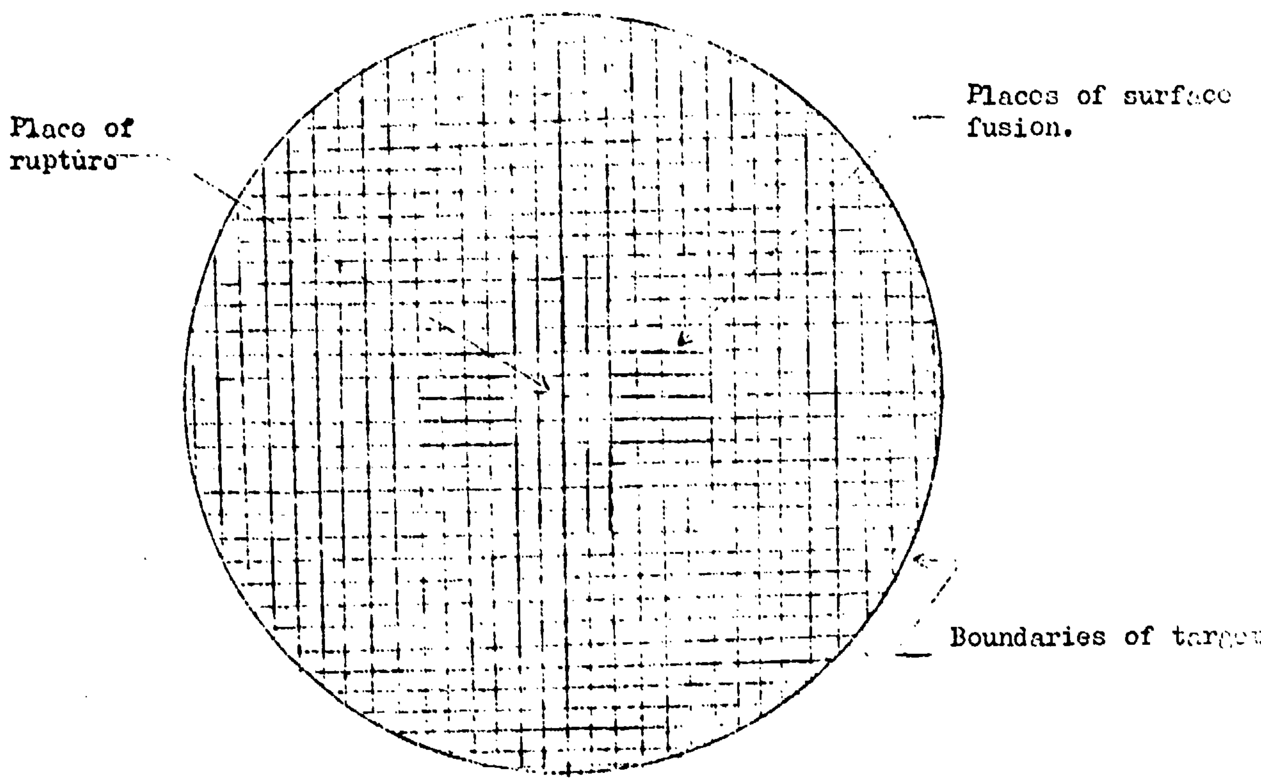
FIG.13 IMPACT FRACTURE OF COTTON FABRIC

Penetrated woven nylon fabric

Fig. (14) shows the SEM photographs of the impact zone in the fabric. The fabric fracture shows the rupture of both warp and weft threads intersecting the impact zone. In this fabric no plug was removed from the fabric, presumably due to the effect of impact on the weakening of the threads at the impact point, leading to the initiation of rupture at this point. The presence of fused fibre ends could show the effect of the high rate of straining on the heating of the broken fibres to the extent of fusion. This fusion could also be due to the rubbing of the pellet with the ruptured yarns during its passage at a high speed through the hole penetrated in the fabric.

The high rate of straining in the yarns involved in the impact zone causes excessive inter-yarn friction.

This excessive friction could cause surface fusion of the nylon filaments as can be seen in fig. (14f). The yarns which are not involved in the impact zone and do not make contact with the pellet show no surface damage due to fusion by friction. The following diagrammatic sketch illustrates the expected places to be damaged by frictional fusion of fibres:



Impact zone of penetrated woven nylon fabric.

Fig. (14) (impact velocity 146m/sec).

a. - Fabric fracture at the impact zone, showing rupture of both warp and weft yarns.

b. - Fractured nylon filaments in the ruptured yarn at the impact zone.

c. - Fractured filament ends fused together at the impact zone.

d. - A group of fractured and fused filament ends at the impact zone.

e. - Surface of filaments in the yarns not involved in the impact zone, showing no sign of surface damage or fusion.

f. - Surface of filaments in the yarns involved in the impact zone, showing fusion along its length due to inter-yarn friction.

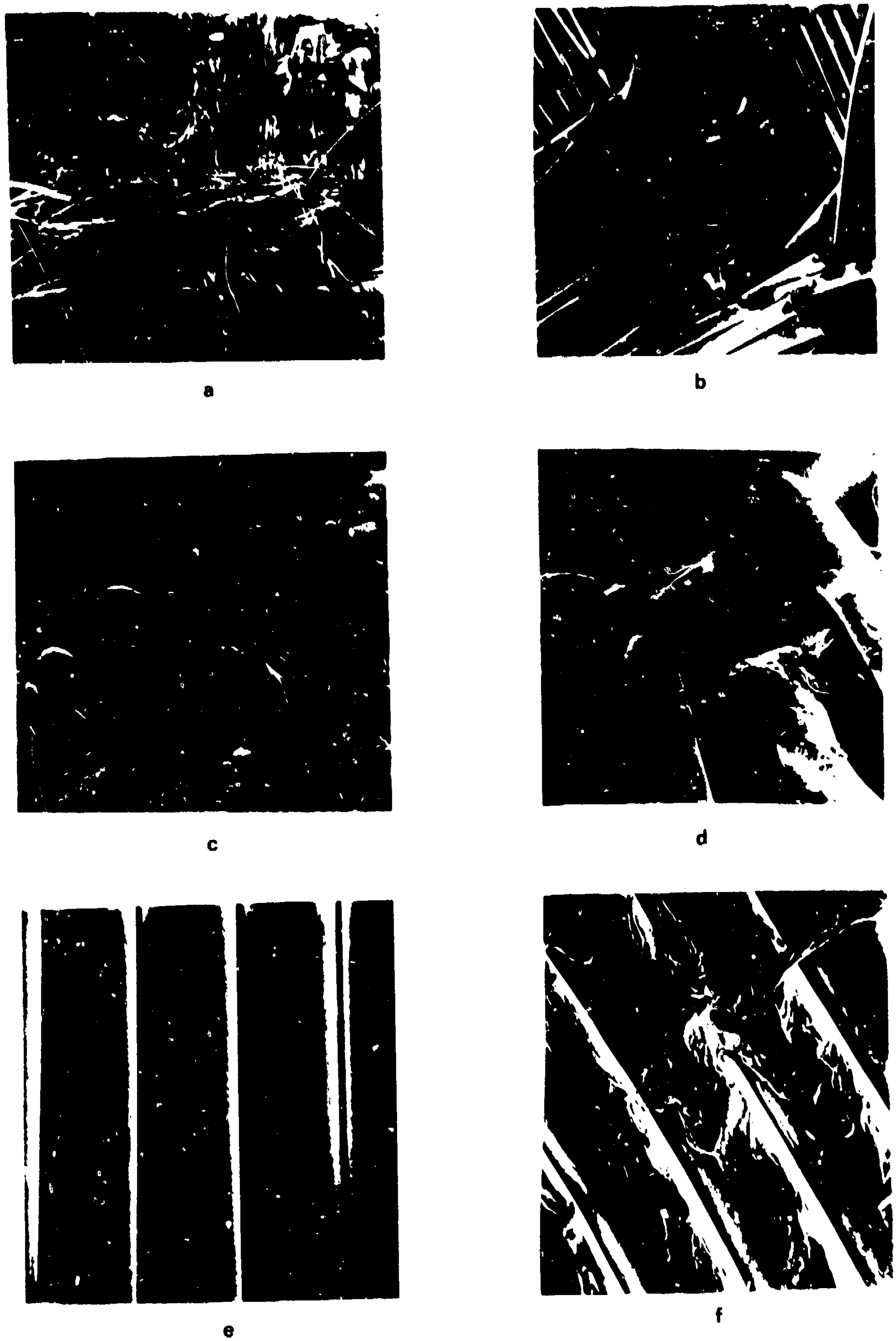


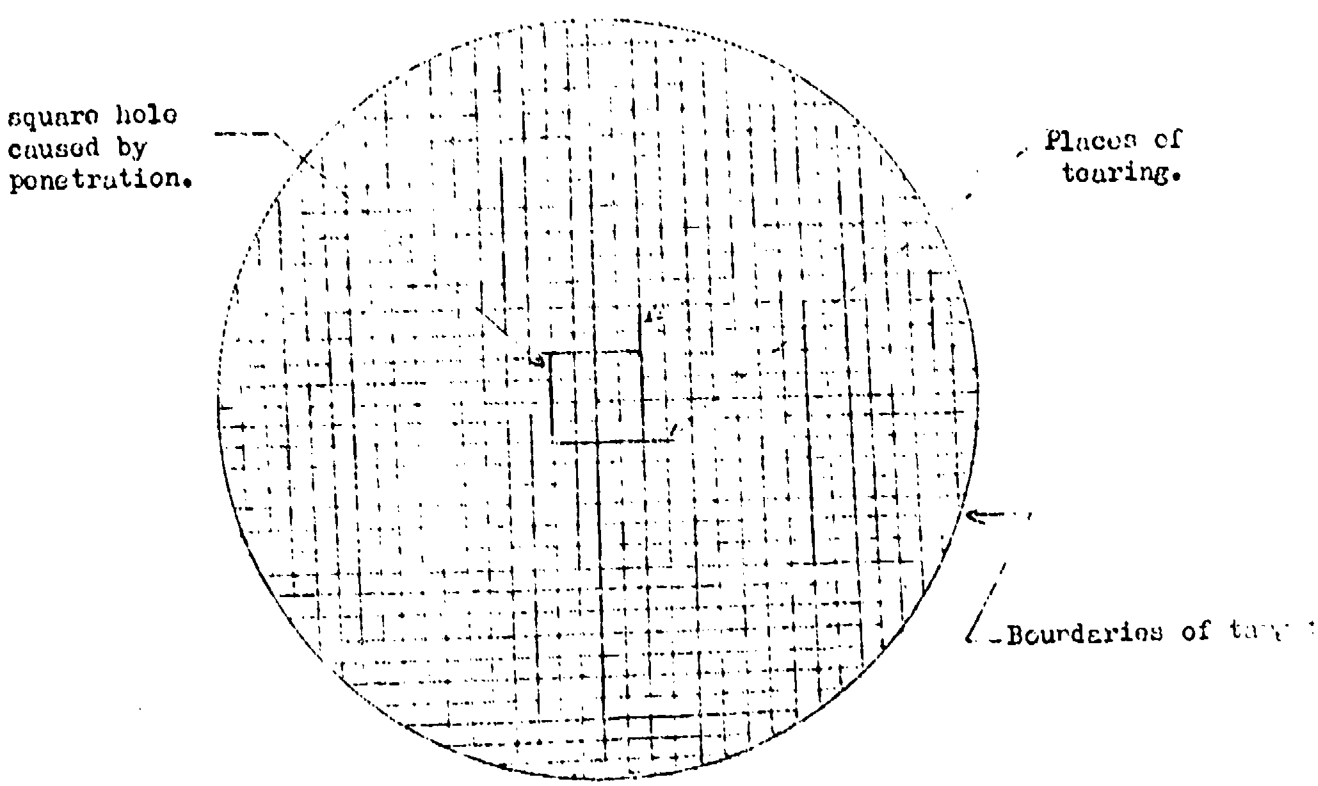
FIG. 14 IMPACT FRACTURE OF WOVEN NYLON FABRIC

Penetrated warp knitted nylon fabric

Fig. (15) shows the SEM photographs taken for the impact zone in the warp knitted nylon fabric. The fracture of the yarn seem to be at the curved part of the loop. Some of the broken filament ends were fused and stuck together, but this was to a less extent than in the woven nylon fabric. Surface fusion of the filaments was also observed near the impact zone, in the yarns involved in the rupture.

Penetrated woven steel fabric

Fig. (16) shows the SEM photographs of the woven steel fabric taken at the impact zone. The fracture of the steel wires intersecting with the impact zone occurred at the cross-over points on the impact face of the fabric. The straining of the steel wires intersecting the impact zone causes damage to these wires at cross-over points near the impact zone. The steel fabric showed tearing at two corners of the square hole caused by penetration as illustrated in the following diagrammatic sketch.



Impact zone of penetrated warp knitted nylon fabric.

Fig. (15) (impact velocity 146 m/sec)

a. - Fabric fracture at the impact zone, showing ruptured yarns.

b. - Disturbance of the knitted loops at the impact zone.

c. - Fractured nylon filaments in one of the ruptured loops, showing fracture at the curved part of the loop.

d. - Fractured nylon filaments fused together at the impact zone.

e. - Surface of yarn involved in impact fracture, showing fusion along the length of the yarn near the cross-over point.

f. - Surface fusion of nylon filaments in the removed plug.

FIG. 15 IMPACT FRACTURE OF KNITTED NYLON FABRIC

Impact zone of penetrated woven steel fabric.

Fig. (16) (impact velocity 140 m/sec)

a. - Edge of the fractured square hole in the fabric, showing local bending of the steel wires at cross-over points.

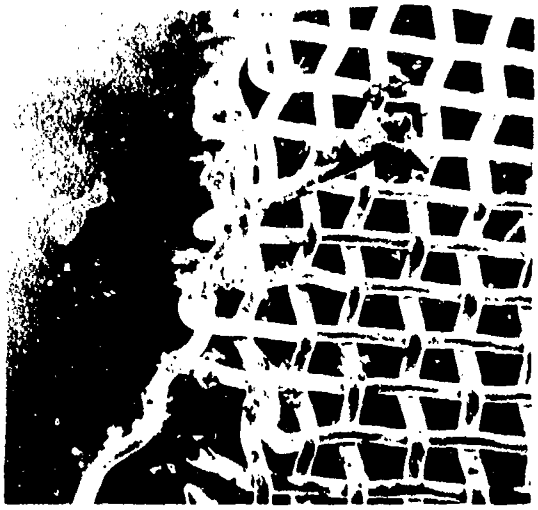
b. - Damage and distorsion of the steel wires in the impact zone.

c. - Fracture and damage of the steel wires at the cross-over points facing the impact side.

d. - Tearing in the fabric around the impact zone, showing fracture of the steel wires at similar cross-over points facing the impact side.

e. - Plug of fabric carried away with the pellet, showing fracture of wires at similar cross-over points.

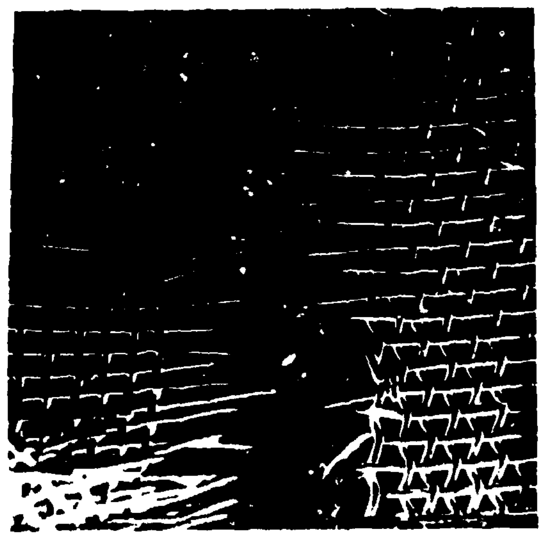
f. - Shape of fractured end of the steel wire in the plug, showing the shear effect at the cross-over points.



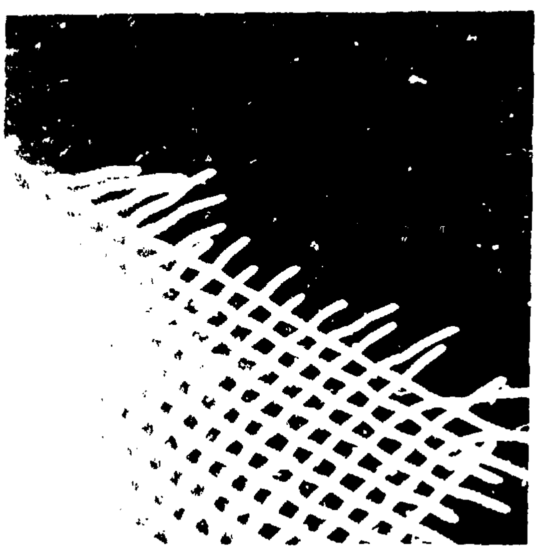
a

b

c



d



e

f

FIG.16 IMPACT FRACTURE OF WOVEN STEEL FABRIC

Penetrated polyethylene sheet:

The SEM photographs for the impact zone of the polyethylene target are shown in fig. (17). This material shows high plastic deformation at the impact zone. In the multilayer target, the plastic deformation was higher in the back layer than the front one. The cross-section of the plug of this target, shown in fig. (17e) shows that the back layer has more drawing effect and more thinning out than the front layer.

Unpenetrated woven nylon fabric.

Fig. (18) shows the SEM photographs of the woven nylon fabric after impact without penetration. The impact zone shows that the impact of the pellet caused the complete fracture of one of the warp threads and partial fracture of other warp threads, but no fracture in the weft threads (due to the high crimp in weft relative to warp). This could show that it is the fracture of the warp threads which initiates the fabric rupture in penetration. Fig.(18,b) shows the squashing of the weft thread which was under the fractured warp thread. This squashing should have also affected the fracture of the missing warp thread, which was appearing on the impact face at the squashing point before rupture.

Unpenetrated woven Kevlar fabric.

Fig. (19) shows the SEM photographs of the unpenetrated woven Kevlar fabric. The impact zone shows distortion of the threads in the fabric but to a small extent not sufficient to create a hole for the pellet passage. The Kevlar fibres at the impact zone, showed surface damage due to splitting tendency of the fibres.

Impact zone of penetrated polyethylene sheet.

Fig. (17) (impact velocity 146m/sec)

a. - End view of the impact zone in the first layer of a multilayer target, (6 sheets), showing plastic deformation around the impact zone.

b. - End view of the impact zone in the 6 th layer of the target, showing more plastic deformation that the first layer.

c. - Top view of the penetrated hole in the first layer.

d. - Top view of the penetrated hole in the last layer, showing smaller hole size than the first layer.

e. - Cross section of the plug of the multilayer target, carried away with the pellet, showing more thinning out of the last layer than that in the first layer.

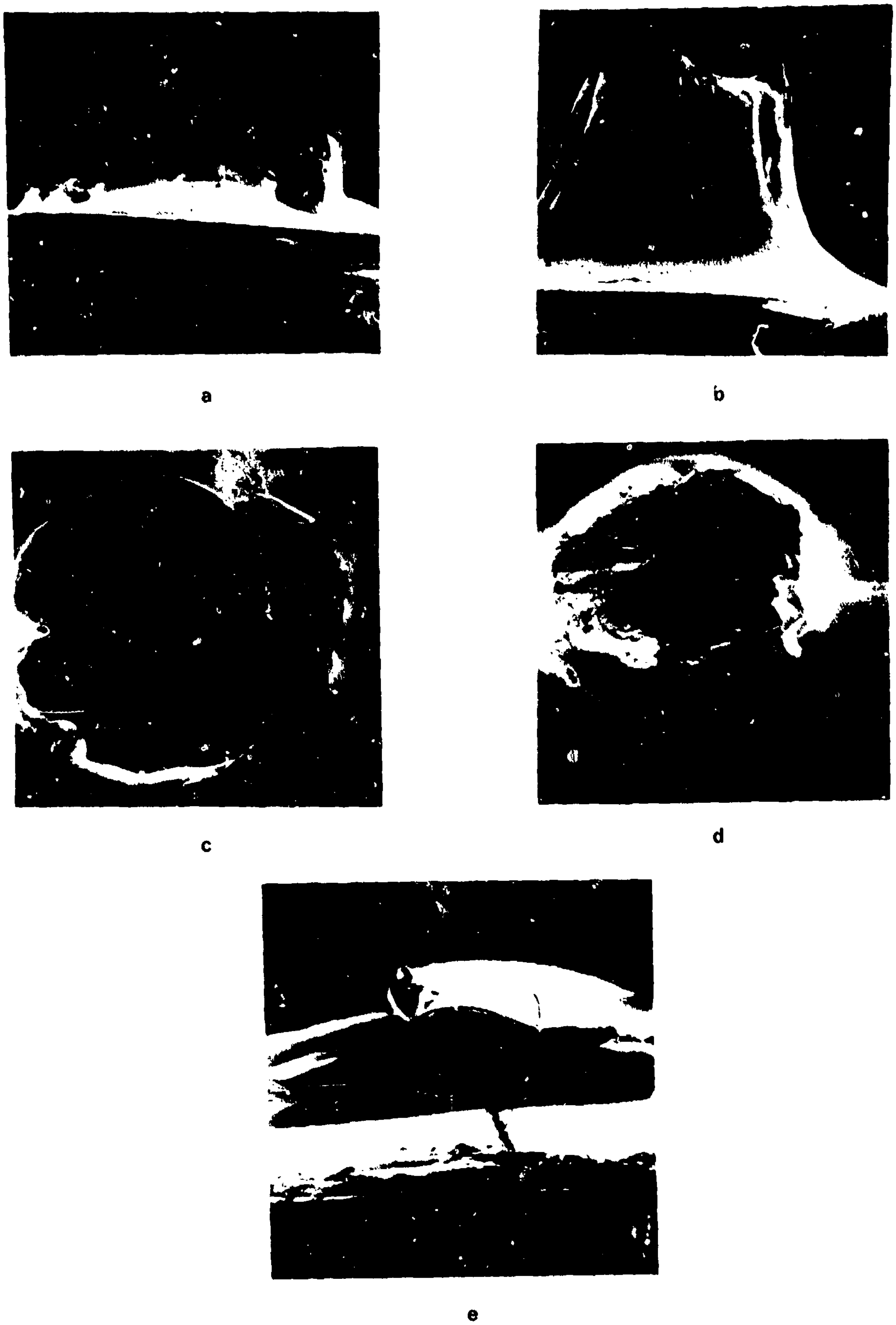


FIG.17 IMPACT FRACTURE OF POLYETHYLENE SHEET

Impact zone of unpenetrated woven nylon fabric.

Fig.(18) (impact velocity 100m/sec).

a. - Impact side of the fabric, showing distortion of both warp and weft threads, and missing of one warp thread at the impact zone.

b. - Distorsion and squashing of threads at the impact zone, and some of the filaments in the ruptured yarn showing on the face of the fabric.

c. - Back of the fabric showing the ruptured warp thread which is missing on the face.

d. - Back of the fabric, showing rupture of filaments across the yarn, and partial fracture in warp yarns only.

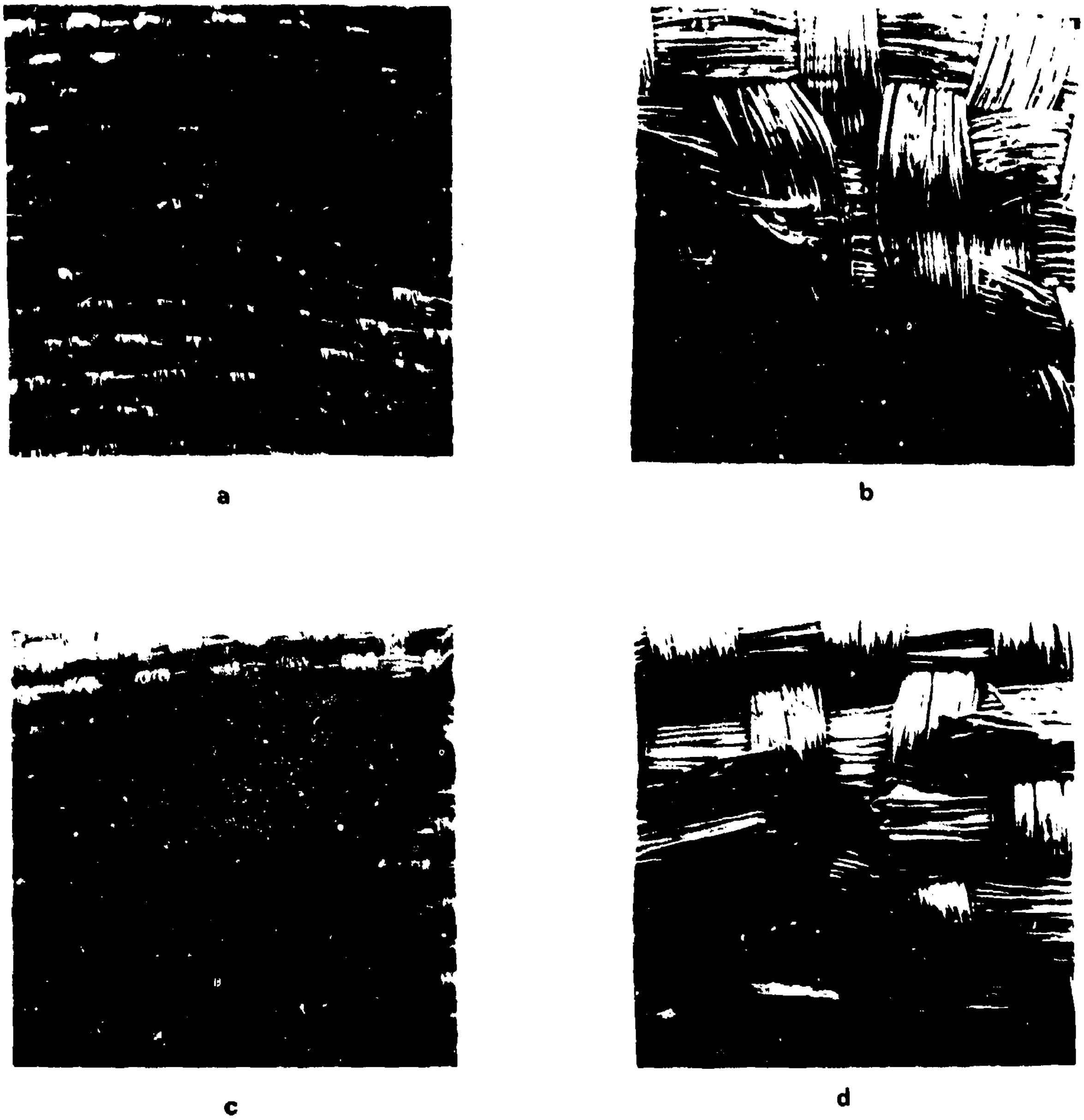


FIG.18 IMPACT DAMAGE IN UNPENETRATED NYLON FABRIC

Impact zone of unpenetrated woven Kevlar fabric

Fig. (19) (impact velocity 146 m/sec)

a. - Distorsion in both the fabric structure and the yarn structure at the impact zone.

b. - Damage of Kevlar fibres at the impact zone.

c. - Fibre splits at the impact zone.

d. - Splitting of Kevlar fibre at the impact zone.

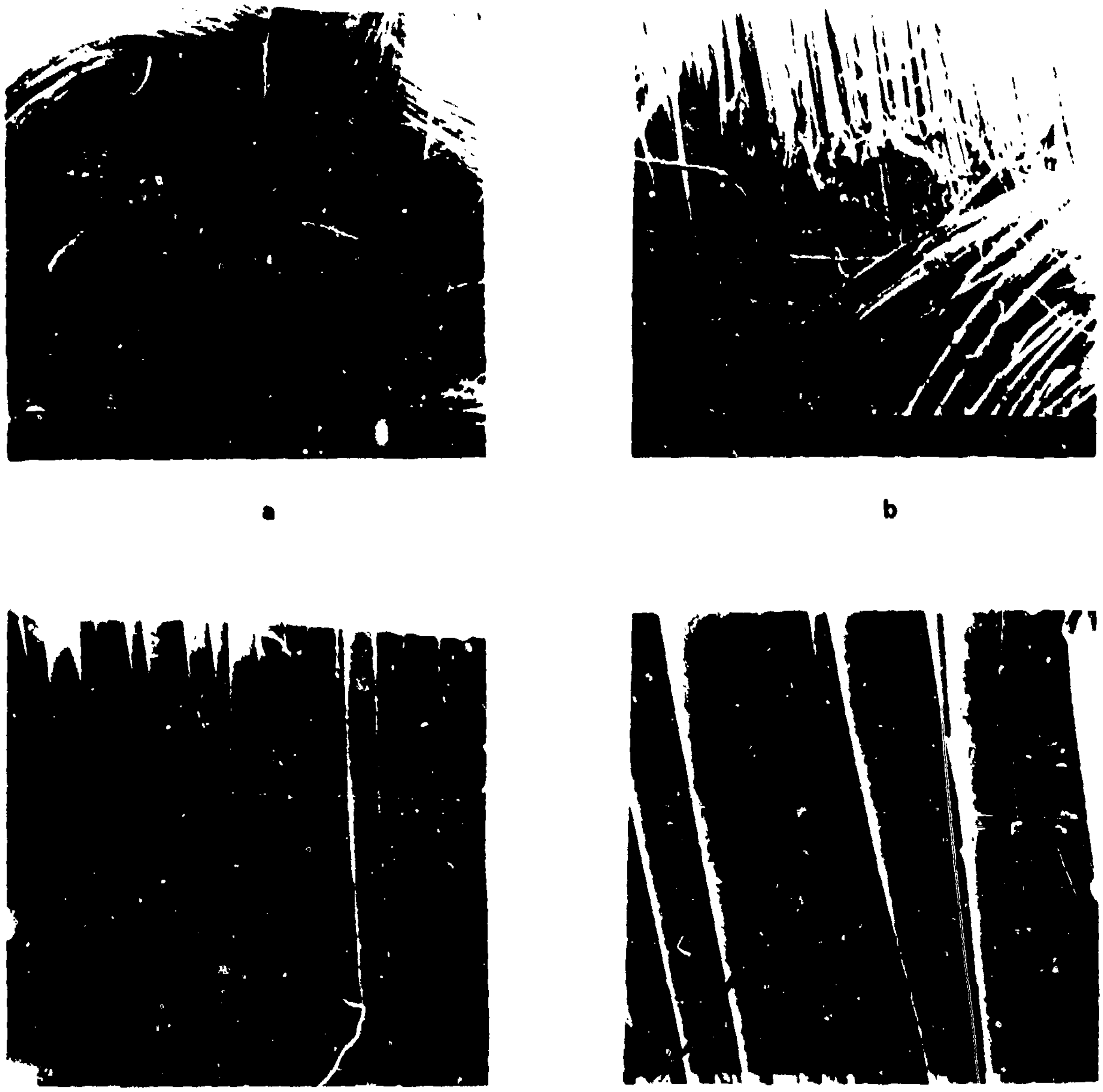


FIG.19 IMPACT DAMAGE IN UNPENETRATED KEVLAR FABRIC

Slow Penetration Tests.

Shape of the load-deformation curve:

Fig. (20) shows typical load-penetration curves recorded on the Instron tester. This type of curve consists of a short initial easy-deformation stage and then the main linear stage with higher resistance to deformation lasting till the fabric is penetrated. The shape of the load-deformation curve in the slow penetration test was, more or less, the same for the different tested fabrics, although the shape of the tensile load-deformation curves of these fabrics differed considerably, as can be seen from the previous figure.

Modulus, strength and extensibility.

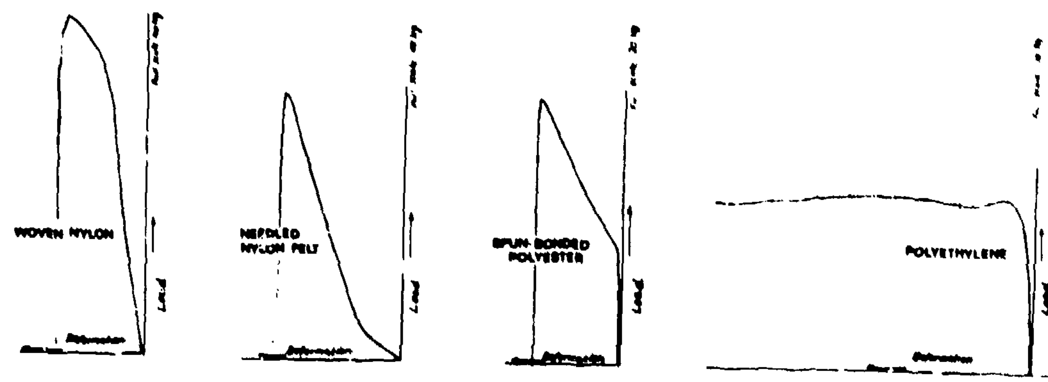
In the slow penetration test, the higher the penetration stiffness of the fabric, the lower was its penetration strength and maximum deformation as can be deduced from table V. In other words, stiff fabrics tended to give a lower penetration strength and a lower maximum deformation.

Table (V) Slow Penetration tests.

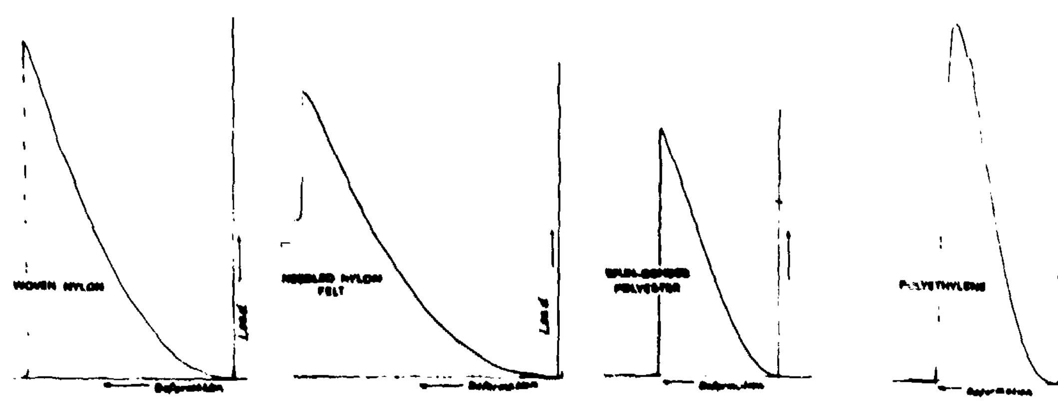
Type of Material	Stiffness g.wt$(g/m^2)^{-1}$	Strength g.wt$(g/m^2)^{-1}$	Maximum bulge strain.	Strength bulge product g.wt$(g/m^2)^{-1}$	Energy Kg.cm/g
1. Paper	359	15.1	.042	0.63	.167
2. Polyethylene	49.9	22	.168	3.7	1.24
3. Woven steel	683	43.7	.097	4.17	1.2
4. Spun-bonded polyester	234	60.5	.138	8.95	2.2
5. Bonded polyester	62	83.3	.21	17.5	4.37
6. Spun bonded polypropylene	347	111	.173	19.2	6.1
7. Bonded nylon	36.6	93	.305	28.4	6.17
8. Woven Cotton	21.5	105	.33	34.6	8
9. Needle felt nylon	25	152	.33	51	13.8
10. Warp knitted nylon	16.5	247	.38	94	17.4
11. Woven nylon	65.5	365	.30	109	28

Penetration Energy:

The area under the load-deformation curve recorded in the slow penetration test represents the energy absorbed by the target. It can be seen from table (V) that the energy of penetration differs according to the type of target material. Stiff high modulus fabrics tend to give lower energy absorption than flexible, low modulus fabrics.



TENSILE LOAD-DEFORMATION CURVES DIFFERING IN SHAPE



PENETRATION LOAD-DEFORMATION CURVES WITH THE SAME SHAPE

FIG. 20 LOAD-DEFORMATION CURVES FOR BOTH TENSILE AND PENETRATION TESTS

The energy absorbed by the fabric in the slow-penetration test was found to be proportional to the energy absorbed in the impact test as can be seen from table VI. This proportionality was found to be approximately linear as illustrated in fig. (21). The fabric which had a high energy absorption in the impact test also showed a high energy absorption in the slow penetration test. This could show that the parameters, mainly influencing the energy absorption in both of the two different tests, are nearly the same.

Table VI Slow-penetration energy and impact energy.

Type of Material	Slow penetration energy kg.cm/g.	Impact penetration energy Kg.cm/g.
1. Paper	.167	.597
2. Polyethylene	1.24	2.9
3. Woven steel	1.2	1.9
4. Spun-bonded polyester	2.2	2.33
5. Bonded polyester	4.37	1.77
6. Spun bonded polypropylene	6.1	4.8
7. Bonded nylon	6.17	4.28
8. Woven Cotton	8	10.8
9. Needle felt, nylon	13.8	18.5
10. Warp knitted nylon	17.4	28.5
11. Woven nylon	28	29.2

Strength-bulge product.

Table (V) shows the relation between the strength bulge product and the energy absorption of the material. The higher the strength-bulge product of the fabric, the higher was its energy absorption as illustrated in fig. (22). This shows that fabrics with high strength and high extensibility in penetration would give a high energy absorption. It should be noted here that a fabric which has a high strength and a high extensibility in the tensile test does not necessarily have the same in the penetration test, because in the penetration test, there is another factor (the shape of tensile stress-strain curve) which plays an important role in determining the penetration strength and extensibility.

Instron tests and dynamic modulus.

Shape of tensile stress-strain curve:

The shape of the stress-strain curve was found to differ considerably from one material to another in the group of materials tested. The stiff fabrics, such as bonded-fibre nonwovens and spun-bonded nonwovens, gave a curve with a steep rise in stress at the start, followed by easy plastic deformation with declining stress towards the breaking point. On the other hand, the flexible fabrics, such as the knitted fabric and the needle felt, gave a curve with a slight increase in stress at the start, followed by more increase in stress towards the breaking point. The work factor could be taken to describe quantitatively the shape of the stress-strain curve (3).

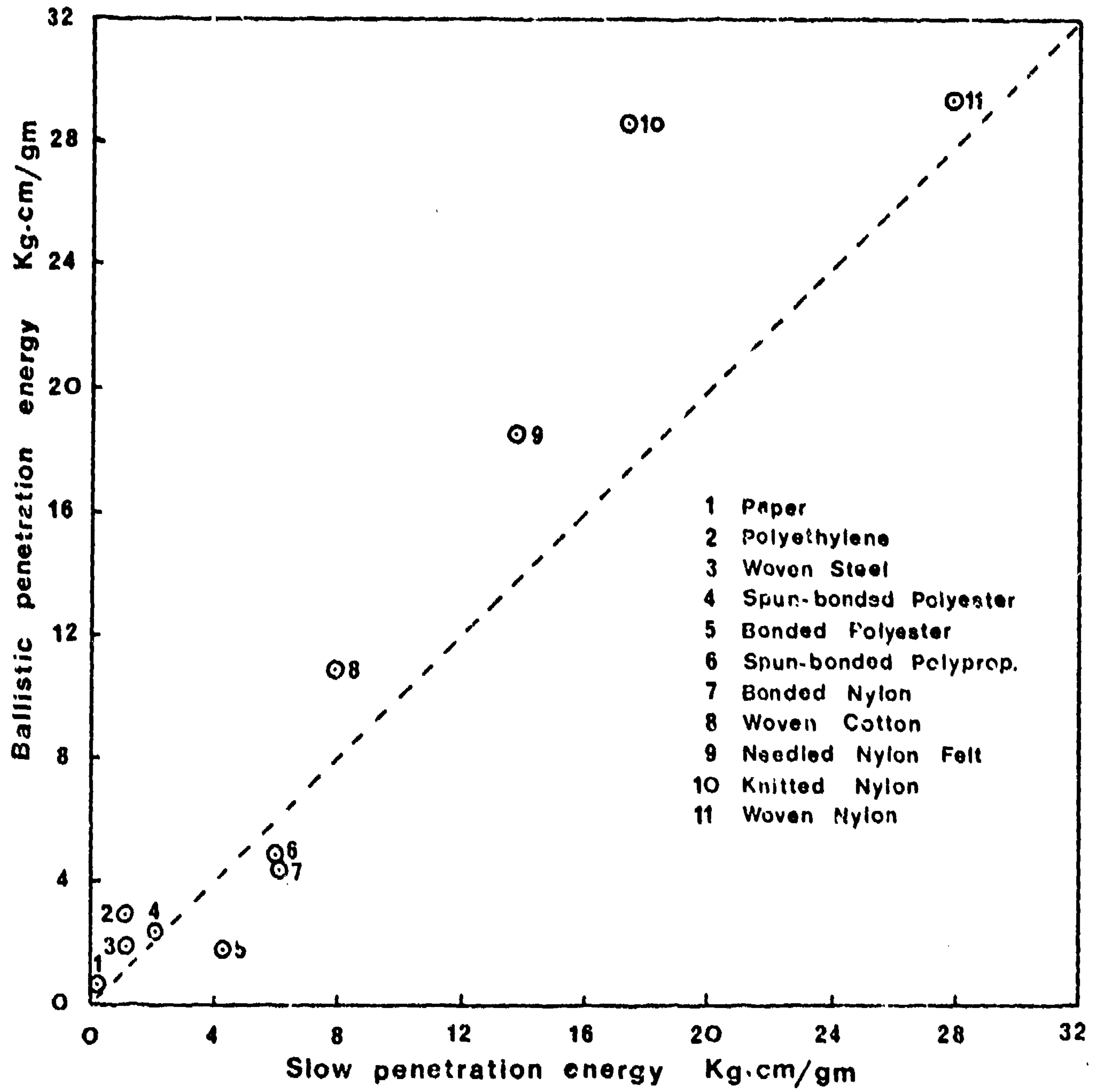


FIG.21 Relation between slow energy and impact energy

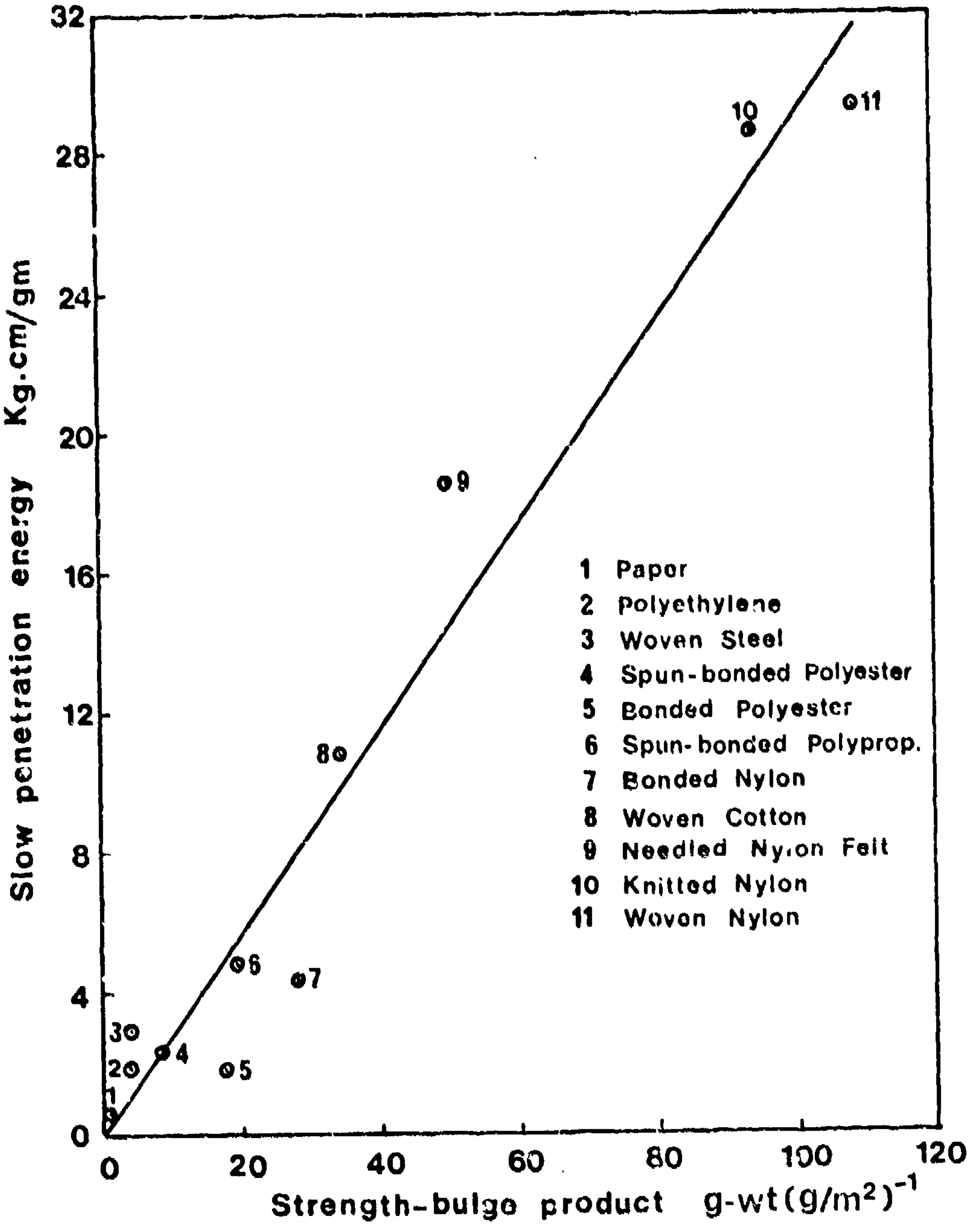


FIG.22 Relation between strength-bulge product and energy in slow penetration

Curves with work factor larger than 0.5 show non-locking deformation, while curves with work factor less than 0.5 show locking deformation.

Comparing the work factor of the material with its energy absorption in penetration, it has been found that the lower the work factor, the higher the energy absorption.

Tensile & dynamic modulus.

Table (VII) shows the Instron tensile properties and the dynamic modulus of the fabrics.

Table (VII) Tensile tests and dynamic modulus.

Type of material	Work factor	Modulus g.wt/tex	Strength g.wt/tex	Breaking ext. %	Energy Kg.cm/g.	Dynamic modulus g.wt/tex
1. Paper	0.52	650	5.67	1.7	4.75	934
2. Polyethylene.	.92	15	2.4	1150	1700	48
3. Woven steel	.75	176	4.65	16	55.8	667
4. Spun-bonded polyester	.69	158	6.5	49	204	126
5. Bonded polyester	.65	15.3	2.27	35.9	55	82
6. Spun-bonded polypropylene	.81	110	5.71	43.4	191	119
7. Bonded nylon	.52	6.3	1.53	32.2	34.6	19
8. Woven Cotton	.35	64.4	5.27	16.4	31.3	61
9. Needle felt nylon	.38	2	5.1	72	143	20
10. Warp Knitted nylon	.29	0.88	7.2	35.9	160	4.4
11. Woven nylon	.5	34.5	13.9	27.8	193	66

It can be seen that the tensile modulus is proportional to the dynamic modulus. The fabrics which have high tensile and dynamic modulus are fabrics which have high penetration modulus. Comparing the modulus with the energy of penetration for the different fabrics, it can be deduced that the higher the modulus, the lower the energy absorption. Although the higher modulus always indicates better strain propagation, it is indicating the contrary in penetration, because the penetration involves large strains and the modulus is not the factor governing the propagation of large strains, but there is another factor which governs the propagation of large strains, namely the shape of the stress-strain curve.

Tensile strength.

Comparing the tensile test with the penetration test, it can be deduced that the fabric with higher tensile strength tends to give higher penetration strength. However, this is not always true, as the modulus has an effect on the penetration. For example, paper and needle felt both have nearly the same tensile strength, but because of the very high modulus of paper it gives considerably lower penetration strength than the needle felt.

Breaking extension.

Comparing the tensile test with the penetration test, it can be deduced that the breaking extension is not proportional to the maximum bulge caused by penetration. The maximum penetration bulge, relative to the breaking extension, depends on the shape of the tensile stress-strain curve as will be explained later in the discussion.

Tensile energy.

The energy absorption in the tensile test was found to be not proportional to the energy absorption in penetration. The ratio of the penetration energy to the tensile energy was dependent on the work factor as can be seen from fig. (23.) The stiff fabrics, with work factor larger than 0.5, gave a low ratio of penetration to tensile energy, while the flexible fabrics showed a high ratio. This showed that the tensile energy alone is not sufficient to indicate the energy absorption in penetration but the work factor is a very important factor determining the energy absorption in penetration.

When the tensile energy was compared with the impact penetration energy, the tensile energy was also found to be not proportional to the impact penetration energy. The ratio of the ballistic penetration energy to the tensile energy was found to depend on the work factor of the material as can be seen from fig. (24). This shows that the shape of the tensile stress-strain curve determines the degree to which the potential tensile energy of the materials could be utilised in both slow penetration and impact penetration.

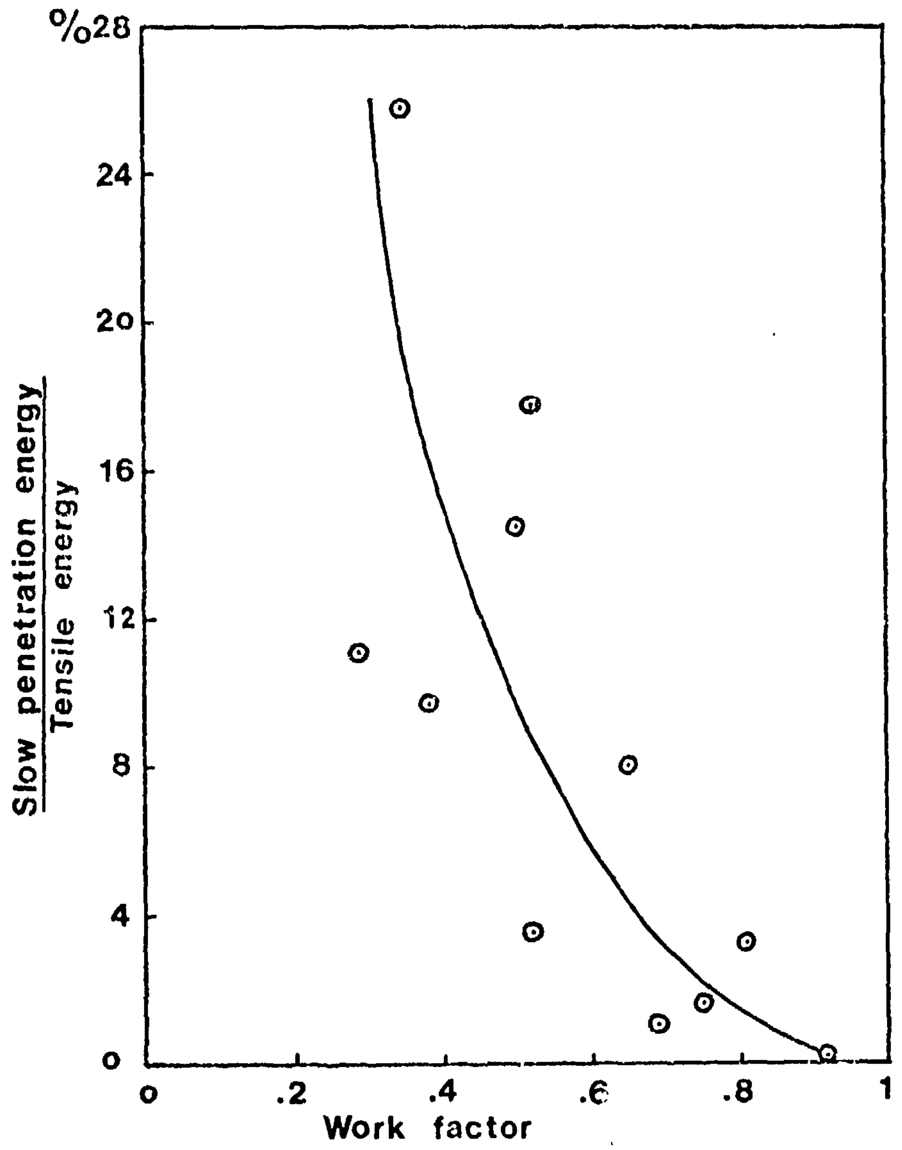


FIG.23 Effect of work factor on energy absorption in slow penetration

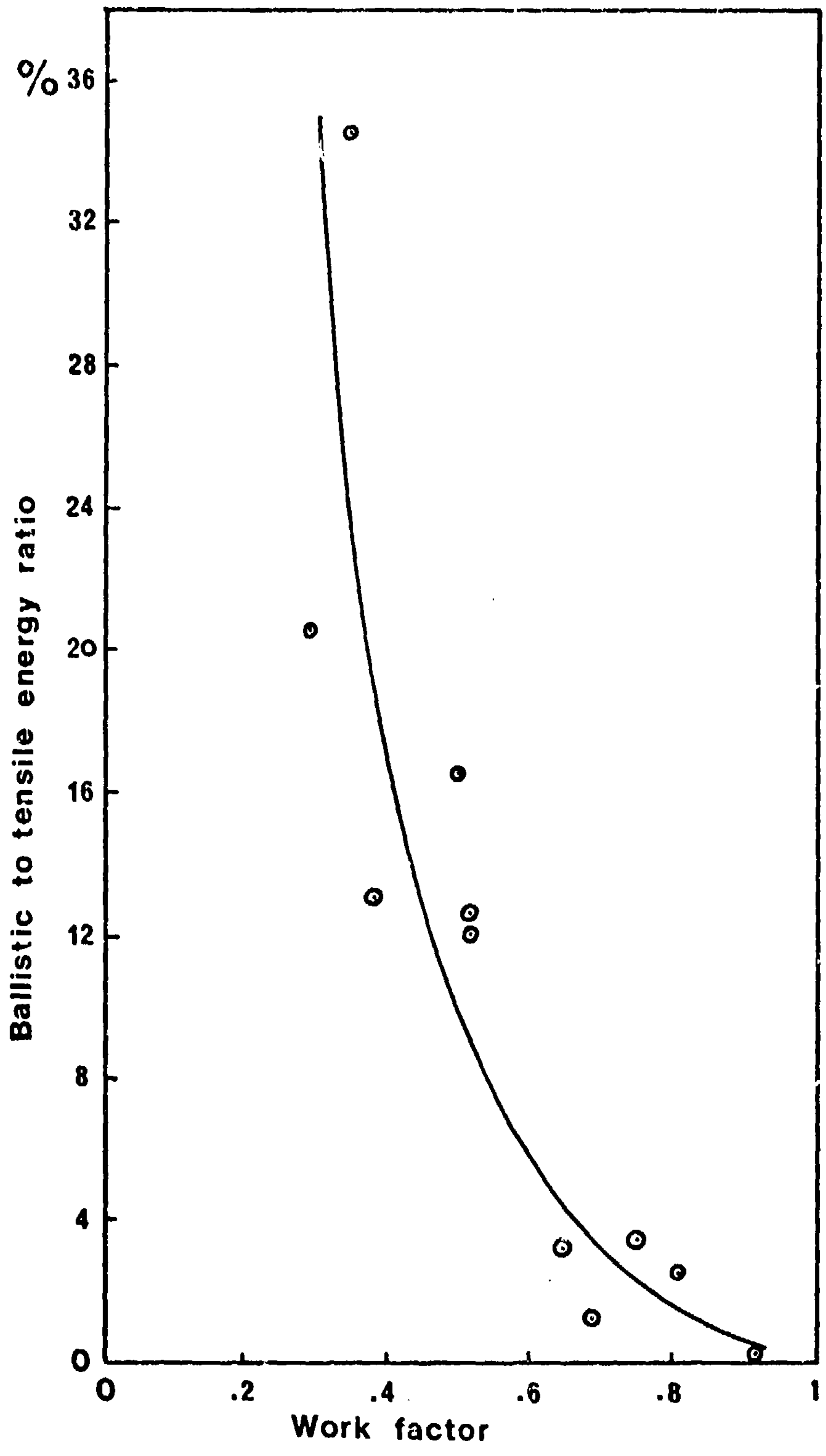


FIG.24 Effect of work factor on energy absorption in impact penetration

Chapter 4.

DISCUSSION.

Understanding of the phenomena of ballistic energy absorption in textile materials demands an understanding of two complicated situations: penetration mechanics and high speed effects. During the second stage of this research, we shall endeavour to follow up these problems with simple theoretical studies. However, at this stage, we present a tentative attempt at qualitative discussion of what happens.

When the fabric is hit by the pellet, the area around the impact point will deform until the rupture strength and strain of the material are reached. If this condition is achieved without substantial propagation of the local strain to the rest of the target, the target will absorb a low amount of energy, mostly due to the deformation of the local impact area. But if the achievement of rupture is associated with the propagation of the large strains to the rest of the fabric, the target will absorb a high amount of energy. This propagation of the large strains to the rest of the target increases the maximum transverse deformation of the target, and accordingly increases the energy absorption. In other words, if two fabrics have the same rupture strength, but one is more efficient in large-strain propagation than the other, this fabric will give higher energy absorption in penetration than the other.

The energy absorption of the material will, therefore, depend on the ability of its structure to facilitate the propagation of large strains, as well as on the penetration strength. The efficiency of the material in large-strain propagation depends on the shape of its tensile stress-strain curve. The shape of the stress-strain curve shows whether the material has a locking or non-locking structure. In the locking structure the increase in the plastic deformation occurring around the impact point is associated with a rise in stress, leading to the propagation of these large strains to the rest of the target. But in the non-locking structure, the increase in plastic deformation around the impact point continues without substantial rise in the stress, leading to no propagation of large strains to the rest of the target.

The two main factors which cause the strain around the impact point to be the maximum strain in the target are: the concentration effect, and the propagation effect. The concentration effect appears in fabrics with random orientation, where the stress decays as we move from the impact point to the boundary of the target due to the increase of the area carrying the load. The propagation effect causes the strain around the impact point to be the maximum as this is the zone firstly deformed in the target, when other zones have not yet known of the deformation. The concentration effect depends on the fibre orientation in the fabric; woven fabrics with biassed orientation in orthogonal directions will give no stress concentration around the impact point, but the stress will be the same from the impact point,

to the target boundary. The propagation effect depends on the shape of the stress-strain curve of the fabric. If the curve indicates a locking structure, this means that the large strains achieved at the impact zone will be associated with the locking of the structure and a higher resistance to deformation. This locking counteracts the advance of large strains due to the impact effect, so that these strains will have the chance to propagate through a great extent of the target. In other words, the locking of the impact zone decreases its rate of deformation, relative to the other zones, and so gives the strain a chance to reach the other zones. The locking structure enables the impact zone to deform plastically, but delays the rise in stress until the strain reaches the other zones and contribute to the maximum deformation of the target. The energy absorption in ballistic penetration of this type of structure is mainly due to the plastic deformation of most of the zones of the target. The needle felt and the warp knitted fabric are good examples of this type of structure.

If the stress-strain curve indicates a non-locking structure, this means that the large plastic strains at the impact zone will be associated with much easier deformation than in the other zones which carry only small strains or have not yet carried any strains. This will cause the rate of deformation at the impact zone to be excessively higher than that at the other zones. The impact zone will, therefore, reach the rupture strain before any large strains have propagated to the other zones in the target. This effect of non-locking plasticity adds to the effect of advancing strains due to impact, and both effects cause the strain at the impact zone to be excessively higher than the strains at the other zones. The impact zone will, therefore, reach the breaking strain of the material before substantial plastic strains have propagated to the other zones in the target. In other words, the non-locking structure causes the impact zone to deform plastically without waiting or giving the chance to the rest of the target to participate in carrying the large strains. The energy absorption in the ballistic penetration of this type of structure is mostly due to the local plastic deformation of the impact zone, while the rest of the target contributes only with small elastic energy, which cannot be compared with the large plastic energy. So, the energy absorption in ballistic penetration of this type of structure is usually very small due to the local contribution, instead of the integral contribution, of the target. The bonded-fibre nonwovens and the spun-bonded nonwovens are good examples of this type of non-locking structure.

The second main factor, influencing the energy absorption in ballistic penetration is the penetration strength of the target. This penetration strength does not only depend on the tensile strength of the material, but it depends also on its modulus. This comes from the nature of the deformation of the impact zone which envolves bending of the structure. This bending will develop tensi[illegible] stresses which add to the tensile stresses already developed in the structure. The magnitude of these bending stresses depends on the modulus of the material. In a very stiff material, the bending stresses are very high, so that the fracture occurs at a low penetration strength compared with the tensile strength. But in a flexible material, the bending stresses are very small so that the fracture occurs at a high penetration strength compared with the tensile strength. Accordingly, if two materials have the same tensile strength, (such as paper and needle felt), the stiffer fabric will give the lower penetration strength. This modulus effect contributes to a greater energy absorption in the penetration of the lower modulus materials than in the higher-modulus materials.

Combining the deformation with the strength of the material in ballistic penetration, it can be deduced that the material which provides a high extensibility combined with a high penetration strength could provide high energy absorption in ballistic penetration. As has been shown, the locking structure is characterised by both high strength and deformation in penetration and accordingly it provides a recommended structure for energy absorption in ballistic penetration. This could lead to the trend in the design of a fabric with a locking-structure providing efficient energy absorption in ballistic penetration.

The fabrics which are constructed from threads, such as woven or knitted fabrics, provide efficient propagation of strain through the target, and even if they are stiff, they provide higher energy absorption than stiff fabrics with a random fibrous structure which lead to higher stress concentrations.

The investigation of the impact zone by the SEM helps in the understanding of the type of damage in the different types of target structures. For example, in the case of stiff non-locking structures, such as the woven steel fabric, damage due to the shearing of fibres was predominant, while in the case of extensible locking-structures, such as the woven cotton fabric, damage due to the tensile rupture of the fibres was predominant.

The investigation of the unpenetrated woven nylon fabric showed that the threads with the lower extensibility (warp threads) started to break before the threads with the higher extensibility (weft threads). This could help in the design of a fabric with equal extensibility in both of the warp and weft directions, to give better share of penetration resistance between the two systems of yarns.

The Kevlar woven fabric, showed that the remarkable high tenacity of Kevlar fibre provided a resistance to the tensile rupture of the fibres, and the fibre damage occurred due to the splitting of the fibres.

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