BEHAVIOUR OF ARAMID EPOXY COMPOSITE STRUCTURES TO BIRD IMPACT

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SUMMARY

Considering the development in Aeronautics of Aramid epoxy (Kevlar) structures, the French STPA has sponsored in CEAT an experimental investigation to know the behaviour of these structures in a bird impact.

The program of the investigation has been presented in the 17th BSCE.

We recall this program, its development and the contribution of the French Aircraft manufacturers.

The results of normal impact are presented both for the Kevlar 49 and partially for the Kevlar 29.

The oblique impact tests, the experimental difficulties encountered and their solution are also shown.

Référence
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1. INTRODUCTION

In Working Paper n°6 of the 17TH B.S.C.E. Meeting, we have presented the French experimental research program on the behaviour of aramid epoxy (Kevlar *) composite structures exposed to bird impacts.

This program is sponsored by the French STPA in CEAT.
The Aircraft manufacturers : Dassault-Breguet Company (AMD-BA) and Aerospatiale Company (SNIAS) have contributed to this research by the supply of test specimens.

These specimens were in relation with the problems encountered in the certification of composite components for the following aircrafts :

FALCON 900	(AMD-BA)	Figure 1
ATR 42	(Aerospatiale)	Figure 2

Today's lecture will present and discuss the results of this experimental research over a two year period (October 1983 - December 1985).

At this date the program concerning the normal impacts is completed.

For the oblique impacts, the AMD-BA test specimens have required a large amount of work.

The delays for delivery of the CEAT rectangular plates (painted) and the test program of the CEAT gun, have deferred the performance of the systematic tests in oblique impact.

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2. DEFINITION OF THE TEST SPECIMENS

The specimens described in Tables 1 and 2 have been built by CEAT (on the STPA program) and the specimens in Tables 3, 6, 7, 8 and 9 by the AMD-BA company.

The designation BZ310 concerns specimens of the STPA program.

The designation BZ410 represents the AMD-BA contribution to the fabrication of test specimens.

The specimens supplied by Aerospatiale are defined in Table 5.

- Table 1 and Figure 3 represent the CEAT monolithic plane plates
- Table 2 : CEAT plane plates sandwich, Figure 4 with one layer of honeycomb, Figure 5 with two layers.
- Table 3 : concerns the sandwich curved specimen with one layer of honeycomb material. These cylindrical specimens, having a small radius of curvature are representative of leading edges (Figure 6).
- Table 4 : defines the sandwich curved specimens with a great radius of curvature (Figure 7) representative of the skin of a radome.
- Table 5 and Figure 8 represent the Aerospatiale leading edges.
- Table 6 presents the AMD-BA specimens used to investigate the influence of the resin and for the first tests with Kevlar 29.
- Table 7 defines the AMD-BA monolithic plane specimens (arrangement of Fabric plies Figure 13).
- The AMD-BA sandwich plane specimens are represented in
  - Table 8 : specimens with impact surface painted
  - Table 9 : specimens with a thin sheet of 2024 aluminium alloy on the impact surface (Figure 9)
- Figure 10 represents a CEAT monolithic square plate modified by bonding of a 2024 plate at the top edge.
  This type of specimen has been used in the first oblique impact tests.
- Figures 11-12-13 show the arrangement of Fabric plies :
  - Figure 11 in sandwich specimens (one honeycomb layer)
  - Figure 12 in sandwich specimens (two honeycomb layers)
  - Figure 13 in monolithic plane plates

  The differences between the various arrangements also reflect the differences between the manufacturers concepts.
- Table 10 : gives the mechanical properties of the fabrics used.

3. TEST MEANS AND IMPACT CONDITIONS

Figure 14 is a general view of the test facility and pressurized air guns of CEAT. The 150mm diameter smooth bore gun only has been used.
The test specimens are supported by two frames :

- Figure 15 : for square plates in normal impacts
- Figure 16 : reclinable support for oblique impacts

Figure 33 : shows the test equipment at the nozzle of the gun, including, from right to left : the device for bird velocity measurement, the test specimen and the high speed camera (2500 frames/second).

The mass of the birds is 1.8 kg.

The birds are either freshly killed or frozen and thawed chickens.

Table 12 : gives the number of shots performed for each type of specimens.

4. RESULTS OBTAINED

4.0 Preliminary note

All results are expressed in terms of bird kinetic energy versus the number of fabric plies of the composite.

The kinetic energy integrates the variations of the bird masses. The relation between the mass of the unit area of the dry Kevlar plies and the number of plies is shown in Figure 30 (bottom curve).

4.1 Normal Impact

4.11 Kevlar 49

4.111 Kinetic energy of penetration

- Figure 17 gives the limit kinetic energy of penetration for the monolithic plane plates in Satin 8 and Figure 18 for the Satin 4. One will remark the proportionality of the kinetic energy of penetration to the number of fabric plies and the sensitivity to the arrangement of the fabric plies.

The Satin 8 style fabric absorbs more kinetic energy than the Satin 4 style. This property is due to the mode of weaving : the woven armor of a fabric of Satin 8 style is more deformable than that of a fabric of Satin 4 style.

- The time the resin impregnated fabrics staid in the workroom has led to the selection of epoxy-resin 145.5 (red) instead of the 145.2 resin (yellow).

- Figure 19 gives the results of tests performed on monolithic square plates (6 fabric plies).

The CEAT plates used as reference are assigned index "C".
The curing pressure seems to have some influence and the results with the resin 145.5 cured at 2.2 bars are about the same as those with the 145.2 resin cured at 3 bars.

- The impact tests on the sandwich specimens (Figures 20 and 21) have exhibited surprising characteristics to wit, for a small number of fabric plies, the strength of a sandwich specimen is equivalent to that of a monolithic specimen with less plies :

3+3 plies is equivalent to 4 plies monolithic
4+4 plies is equivalent to 7 plies monolithic

This particularity is more obvious on the Satin 8 fabrics.
The presence of honeycomb layer(s) reduce the bird impact strength of the composite.

- Figure 22 shows all results obtained with the plane and curved specimens (monolithic and sandwich).

The level noted "K" indicates the strength of the Kevlar alone.
The level noted "S" is that of the entire specimen.

4.112 Energy absorption after penetration

- Figure 23 (for the monolithic plane plates) and Figure 24 (for the sandwich specimens) show another disconcerting characteristic of the Kevlar structures :

Contrary to the metallic structures, the kinetic energy absorbed in the piercing of the plate is lower than the limit energy of penetration and this, one time out of two, by a large amount.

In these figures the ratio (W_a/W_p) of the absorbed energy to the limit energy of penetration, is indicated in terms of the ratio (W_o/W_p) of the initial bird kinetic energy (W_o) to the limit penetration energy (W_p).

The points are grouped along two straight lines :

(1) ...$(W_a/W_p) = 0.53$
(2) ...$(W_a/W_p) = 0.9 \ (W_o/W_p)$

The characteristics of these lines are the failure pattern of the plate :

(1) corresponds to a star shape failure
(2) corresponds to a "paper leaf" shape (noted "book page")

Figure 25 shows these failures for the monolithic plates, Figures 26 and 27 for the sandwich plates.

These failure patterns are also found in the sandwich curved specimens (Figure 28) and in the Aerospatiale leading edges (Figure 29).
For the differents tests corresponding to these figures, Table 12 gives the quantities (W_o/W_p) and (W_a/W_p).

Today we have no satisfactory explanation for this phenomenon.

It seems that line (2) corresponds to the limit failures.
For the results corresponding to line (1), it is difficult to incriminate the boundary conditions.

The vibration of the plate during the bird impact could provide an explanation for the plane specimens but the existence of this vibration cannot be foreseen. In addition this explanation does not seem to be suitable for the sandwich curved specimens.

The property described by line (1) is a drawback in the use of the material. Consequently the philosophy applicable to the use of such structure is either to contain a bird or to let the bird penetrate and to have underlying parts either suffeciently strong or protected by a metallic shield.

4.113 Comparison with 2024 Aluminium Alloy

As one can see the performance characteristics of these Kevlar structures, with regard to bird impact, are not remarkable. The comparison, at a same mass of unit area, with plates in 2024 aluminum alloy is given in Figures 30 and 31.

The columns in blue represent the bird kinetic energy limit of penetration of plates of equivalent thickness (middle curve of Figure 30).

For the thin plates the metal withstand twice the same energy as Kevlar. These results have been obtained on the same test support (Figure 15).

Figure 31 also gives the velocities used in the tests and the corresponding kinetic energy of the 1.8 kg birds.

4.12 Kevlar 29

The Kevlar 29 fabrics are used as shield against the solid projectiles (bullets). But the weavers do not have in their list of products fabrics of Satin 8 and Satin 4 styles.

For the direct comparison of performance between Kevlar 49 and Kevlar 29 in the case of bird impact, the BROCHIER company has had for this purpose to weave and impregnate with 145.2 resin two rolls of material each 100m long, the first one in Satin 8 style with filament yarns of 440 decitex, the second one in Satin 4 style with filament yarns of 1100 decitex.

The mechanical characteristics of these fabrics are given in Table 10.

The Kevlar 29 yarn costs less than the Kevlar 49 yarn. Consequently preliminary impact tests on Kevlar 29 plane plates have been quickly undertaken. AMD-BA company had built three specimens in Satin 8 (Designation Bz 459 A) and CEAT two specimens (Designation : 2467 for Satin 8 fabric and 2466 for Satin 4).

Figure 32 shows the test results and the comparison with Kevlar 49. The kinetic energy of penetration is about the same as that of Kevlar 49 but it seems that the absorbed energy after piercing is greater. We have also to point out that the permanent deformation of the plate resulting from the impact is, in the same conditions, more than twice that of Kevlar 49 plates.

Unfortunately, these first results did not fulfill the expected promises from the former tests with solid projectiles.

4.2 Oblique Impacts

4.21 Background : the problem encountered

If the absorption of the bird kinetic energy has been the unpleasant surprise of the normal impact tests, the shots with oblique incidence have showed another disconcerting property of the Kevlar plates. We have called this property : the sliding of the bird.

The first oblique impact tests have been performed on monolithic plane square plates mounted on the support shown in the right part of Figure 33.

The phenomenon appeared since the very first shots :

For an angle of incidence of 45° the kinetic energy of penetration is about the same as the one in normal impact.

Both the support and the length of the plate have been incriminated. Specimens, as shown in Figure 10, have been made and tested on the reclinable support shown at the left part of Figure 33.

The results were the same but when a sheet of Vacpack film is set on the surface, the component of the bird kinetic energy normal to the plate is at penetration equal to the energy of penetration in normal impact.

Figure 35 shows these first results in the form of normal kinetic energy of penetration versus the number of fabric plies. The coloured contour of the columns indicates the values of the limit penetration energy in normal impact.

Figure 36 represents the results of the tests with Vacpack film (index "V").

Note :

The Vacpack film is a material used to remove the composite pieces from the mould after curing.

The consequence of these first tests was that it was decided to paint the impact surface of the specimens like the aircraft skin.

The completion of the CEAT rectangular specimens was delayed and the corresponding oblique impact systematic tests deferred.

Meanwhile, for the design of the wing root fairings and of the nose of FALCON 900 aircraft, the AMD-BA company had to fabricate rectangular plane specimens, monolithic and sandwich, (see Tables 6,7,8,9) and also sandwich curved specimen (Table 4) which were the first to be fabricated. The tests performed on these specimens represent the major part of the oblique impact test campain.

4.22 Test Conditions

The tests were effected at high angles of incidence from 65 to 72° (grazing shots).

Velocity of 1,8 kg bird : 180 m/s

Bird kinetic energy : 29300 joules

The attachment of specimens to the support was, at first, peripheral (Figure 34). Then after the sandwich curved specimens had been eliminated due to their cost and also because they were too short, each curved specimen was replaced by two plane specimens.

These plane specimens have been tested in two different manners :

In the first one the specimen is attached in the high position (Figure 39) and fastened at the top and bottom.

In the second one the specimen is attached in the low position (Figure 40) so as to leave a gap between the upper edge of the specimen and the border of the support, to let the bird go through.

In this case the attachment is lateral only.

These tests with two modes of attachment represent the best compromise found to take into account the influence of the curvature of the actual aircraft parts.

Note : In Figures 39 and 40 the support has been set slightly more upright to take the photograph.

4.23 Test results

The painting of the impact surfaces either like the aircraft skin (C.7999 + PU 66) or with a paint incorporating Teflon (CELOGLISS) has not solved the problem of the sliding of the bird.
Only those tests specimens with a 2024 sheet bonded to the impact surface (Figures 9, 39 and 40) have eliminated this problem.
Before giving the results we must say that in our opinion, the words "Sliding of the bird" account for the property of the target to be "locally deformable". But because of the the thickness of the support we have never been able to see this deformation.

The test results on monolithic plane plates have been grouped together with the preliminary tests in Figure 35.

Figure 41 shows the results on the sandwich specimens, both plane and curved. The honeycomb material is glass, designated as "C" or 5056 aluminum alloy, designated as "A". Specimens 33a and b include carbon fabric plies and the impact face of specimens 34a and b is made of five plies of aluminum wire fabric.

For each test the coloured columns give on the left the total bird kinetic energy and its component normal to the target, on the right the energy absorbed with its components, both tangent and perpendicular to the plate.

For specimens 20a, 20b, 23a and b, 34a and b, the left group of two columns refer to a test in the top and bottom attachment condition, the right group to a test in lateral attachment condition. In all these tests the bird had penetrated.

Specimen 11 after impact is shown in Figure 38. The failure at the upper part is due to the presence of the support (as in Figure 37) and indicates that the specimen is too short.

Figure 42 shows, with the same conventions as in the preceding figure, the energy absorption for the sandwich specimens with a 2024 aluminum alloy skin. The yellow index "C" indicates a bird containment or penetration limit. The blue index "C" indicates an absolute bird containment.

These show that specimens 32 and 29, respectively tested with top and bottom and with lateral attachments, are the only ones to have contained the bird (in the two test configurations).

But the material of the honeycomb core (5056 aluminum alloy) was not suitable for a nose cone on account of the lightning-strike hazard. Therefore a curved specimen (Figure 43) has been built of same composition as specimen 21. The influence of the curvature compensates for the light deficiency resulting from the association of .6mm thick sheet and glass reinforced polyester honeycomb.

Figure 44 shows the frames of the shot's picture and it can be seen that the bird glances off the skin.

It must be said that the applications of all these specimens have not been developped because the thermal coefficients of expansion of Kevlar (negative) and aluminum alloy (positive) are too different from each other.

5. CONCLUSION

The presentation of these results does not go without some disappointment or at least regrets because great hopes had been placed on Kevlar to withstand bird impacts.

The characteristics found concerning the energy absorption reduces the benefit of the use of this material.

On other hand we do not know the degree of generality of the results given. The scattering of specimens is pratically unknown.

The gun also is not a very faithful tool. The obtainment of the hoped velocity proceeds more from the art or the luck of the gunner than from pure and cold science. Thus the limit values can be tainted with some dubiousness.

In addition for the oblique impacts each specimen has been subjected to one shot only. One can reasonably wonder whether the results obtained are not a mere collection of peculiar cases.

The behaviour of the specimens as a locally deformable target, perhaps due to the thinness of the plates, will create experimental difficulties in the systematic oblique impact tests on the CEAT rectangular plane specimens, both in the test stage and in the analysis of test results.

Without excessive pessimism, one can fear that the outcome will be poor and therefore the use of these results in the design of a new structure will not make obsolete the performance of bird impact tests on actual specimen representative of the aircraft part.

However the experimental work achieved should be considered as giving useful data for the clarification of future problems.

T A B L E S

TABLE 1 - CEAT MONOLITHIC PLANE PLATES

NUMBER OF SPECIMENS

MATERIAL		KEVLAR (R) 49				KEVLAR (R) 29	
FABRIC		SATIN 8		SATIN 4		SATIN 8	SATIN 4
STYLE		DU PONT 181 NL-5,2233		DU PONT 285 NL-5,2234			
BROCHIER DESIGNATION		788		914		E 24,78 (SPECIAL	E 24.77 WEAVING)
RESIN EPOXY		145.2 (54,5%)		145.2 (54%)		145.2 (54,5%)	145.2 (54%)
SHAPE		SQUARE	RECT.	SQUARE	RECT.	SQUARE	SQUARE
NUMBER OF PLIES	6	5	4	4	2	6 (1 *)	6 (1 *)
	8	5	4	4	2	6	6
	12	4	4	4	2	6	6
	16	4	0	0	0	0	0

SIZES OF SPECIMENS : SQUARE = 475 x 475 (MM) RECTANGULAR = 475 x 700 (MM)

THE FACE OF IMPACT OF THE RECTANGULAR SPECIMENS IS PAINTED.

* : NUMBER OF SPECIMENS MADE AT 12-31-1985
(R) : DU PONT'S REGISTERED TRADE MARK

TABLE 2 - CEAT PLANE PLATES SANDWICH

MATERIAL : KEVLAR(R)49 EPOXY RESIN 145.2 (54%)

HONEYCOMB CORE : NOMEX(R) 3/16 4.5

NUMBER OF SPECIMENS

NUMBER OF HONEYCOMB LAYERS	1				2		
THICKNESS OF HONEYCOMB	7,5MM		20MM		T = 20MM EACH		
FABRIC	SATIN 8		SATIN 4		SATIN 4		
STYLE	DU PONT 181 NL-5,2233		DU PONT 285 NL-5,2234		DU PONT 285 NL-5,2234		
NUMBER OF PLIES	3+3	4+4	4+4	6+6	3+3+3	4+4+4	5+5+5
NUMBER OF SQUARE SPEC.	4	4	4	4	4	4	4
NUMBER OF RECT. SPEC.	2	2	2	2	0	0	0

SIZES OF SPECIMENS : SQUARE = 475 x 475 (MM) RECTANGULAR = 475 x 700 (MM)

THE FACE OF IMPACT OF THE RECTANGULAR SPECIMENS IS PAINTED.

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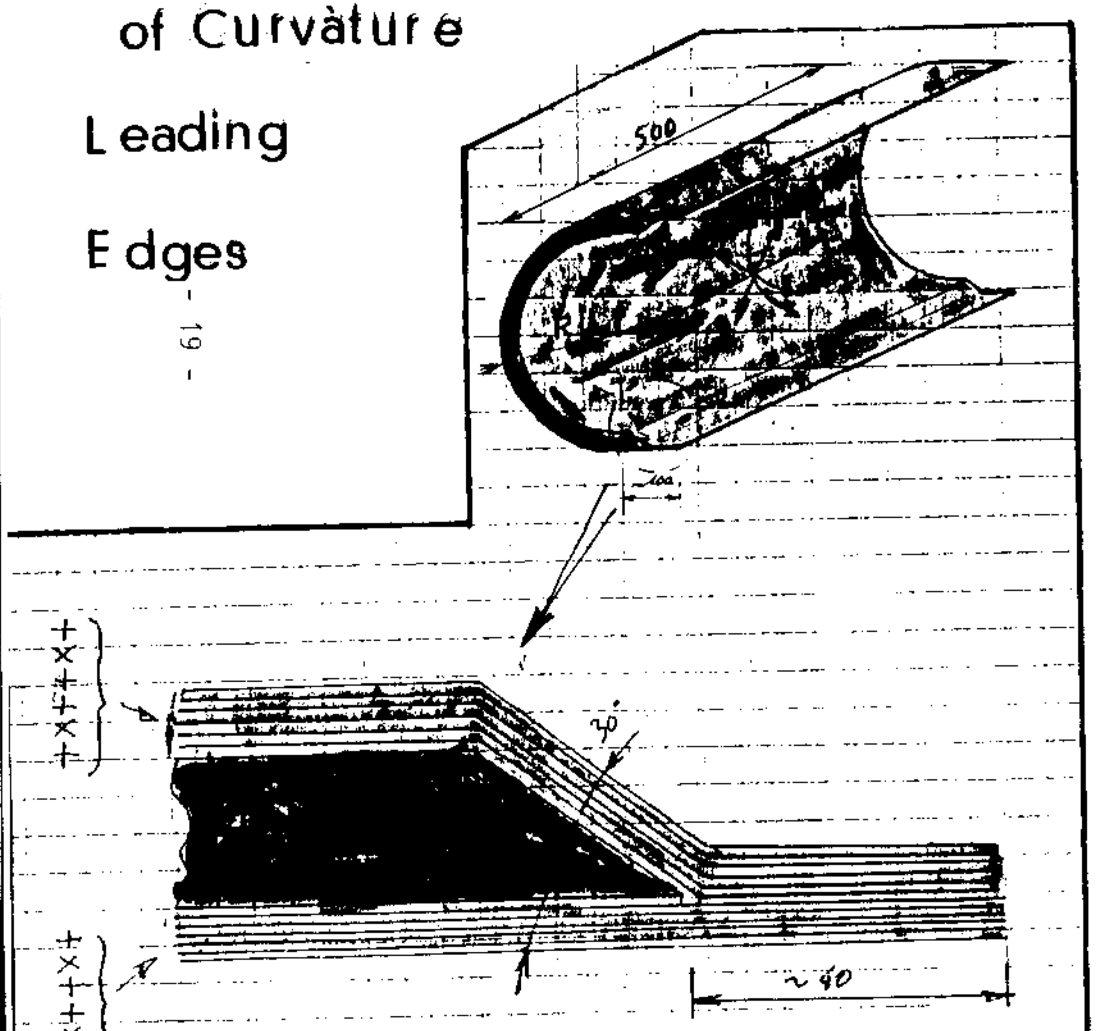
TABLE 3

SANDWICH CURVED SPECIMENS (ONE LAYER OF HONEYCOMB)

FABRIC KEVLAR® 49 Satin 8 Ref 788 (Brochier Ind
RESIN Epoxy 1452 (54 %)
HONEYCOMB HEXCEL NYLON HRH 10 / F 505.0

Small Radius of Curvature Leading Edges



[redacted] SPECIMENS

R (mm)	Number of Fabric Plies 6+6	AMD BA Designation Bz 310 Rep
100	2	1
200	2	2
300	2	3

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TABLE 4 - AMD-BA SANDWICH CURVED SPECIMENS (ONE LAYER OF HONEYCOMB)

WIDE CURVATURE RADIUS R = 750MM

MATERIAL : KEVLAR(R) 49

HONEYCOMB CORE : HEXCEL GLASS NP THICKNESS 7,7MM

AMD-BA DESIGNATION	BZ310 REP.1	BZ404 REP.11	BZ404 REP.14	BZ404 REP.15
HONEYCOMB	NP 3/16-6.0	NP 1/4-6.0	NP 1/4-6.0	NP 1/4-6.0
FABRIC	SATIN 8 NL-5.2233	SATIN 4 NL-5.2234	SATIN 8	SATIN 4
BROCHIER DESIGNATION	788	914	788	914
RESIN EPOXY	145.2 (54,%)	145.5 (54%)	145.5 (54 %)	145.5 (54%)
NUMBER OF KEVLAR PLIES	3+3	3+3	6+3	6+3
NUMBER OF SPECIMENS	2	2	2	2

ALL THE SPECIMENS ARE PAINTED ON THE IMPACT FACE.

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TABLE 5 - AEROSPATIALE LEADING EDGES

SANDWICH SPECIMENS WITH NOMEX(R) HONEYCOMB CORE

FABRIC KEVLAR(R) 49 (SATIN 4) REF. A.S. PQ 10139.143.00

AEROSPATIALE DESIGNATION	1041	5006.15	SPECIMEN N° 2
NUMBER OF FABRIC PLIES	4+3+4	11+3	7+3+7
NUMBER OF HONEYCOMB LAYERS	2	1	2
THICKNESS OF EACH HONEYCOMB LAYER	20+20MM	20MM	15+15MM
MATERIAL DESIGNATION (HONEYCOMB)	NOMEX HRH 3/16 3.0		NOMEX 4.48

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TABLE 6 - AMD-BA MONOLITHIC PLANE SPECIMENS

SQUARE PLATES 475 x 475 (MM)

NUMBER OF FABRIC PLIES : 6

AMD-BA DESIGNATION	BZ404 24	BZ404 25	BZ404 26/26BIS	BZ404 27		BZ459 A
MATERIAL	KEVLAR(R)49					KEVLAR(R)29
FABRIC	SATIN 8	SATIN 8	SATIN 4	SATIN 8		SATIN 8
BROCHIER DESIGNATION	788	788	914	788		E24.78
RESIN EPOXY	145.2(54,%)	145.5 (54%)	145.5(54 %)	145.5 (54%)		145.2(54%)
CURING PRESSURE(BARS)	2.2	2.2	2.2	7		2.2
NUMBER OF SPECIMENS	2	2	4	2		3

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TABLE 7 - AMD-BA MONOLITHIC PLANE SPECIMENS

RECTANGULAR PLATES 600 x 900MM

MATERIAL KEVLAR(R)49 EPOXY RESIN 145.5 (54%)

AMD-BA DESIGNATION	BZ404 REP.13	BZ404 REP.18	BZ404 REP.19	DTM857/85 REP.18BIS	BZ404 REP.35	BZ404 REP.37
FABRIC	SATIN 4	SATIN 8	SATIN 4	SATIN 8	SATIN 8	SATIN 8
BROCHIER DESIGNATION	914	788	914	788	788	788
NUMBER OF FABRIC PLIES	6	6	6	6	16=11 IMPREGNATED +5 DRY	12=9 IMPREGNATED +3 DRY
ARRANGEMENT OF PLIES*	AMD-BA 1	AMD-BA 2	AMD-BA 2	CEAT	**	*CEAT*
NUMBER OF SPECIMENS	2	1	1	2	2	2

* FIGURE N° 13 INDICATES THE ARRANGEMENT OF PLIES

ALL THE SPECIMENS ARE PAINTED ON THE IMPACT FACE

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TABLE 8 - AMD-BA SANDWICH PLANE SPECIMENS

WITH HONEYCOMB CORE (THICKNESS 7,7MM)

MATERIAL KEVLAR(R)49 SIZE OF PLATES 600x900MM

RESIN : EPOXY 145.5 (54%)

AMD-BA DESIGNATION	BZ404 REP.16	BZ404 REP.17	BZ404 REP.20A	BZ404 REP.20B	BZ404 REP.23A	BZ404 REP.23B	BZ404 REP.34
FABRIC / BROCHIER	SATIN 8 (788)	SATIN 8 (788)	SATIN 8 (788)	SATIN 8 (788)	SATIN 8/788 CARBON/G803	SATIN 8/788 CARBON/G.803	SATIN 8/788 ALU:401 (145.5 60%)
NUMBER OF FABRIC PLIES	6+3	3+3	6+3	6+3	(3K+3C) +(3K+1C)	(3K+3C) +(3K+1C)	5. ALU + 6+3
ARRANGEMENT OF PLIES	AMD-BA	AMD-BA	AMD-BA	AMD-BA	AMD-BA*	AMD-BA*	CEAT
HONEYCOMB CORE HEXCEL REF	GLASS NP3/16 6.0	GLASS NP3/16 6.0	1/8-5056 .0015 6.1	1/8-5056 .0015 6.1	GLASS NP3/16 6.0	GLASS NP3/16 6.0	GLASS NP3/16 6.0
TOP COAT (PAINT)	C9999+PU66	C9999+PU66	C9999+PU66	CELLOGLISS	C9999+PU66	CELLOGLISS	CELLOGLISS
UPPER EDGING	HARDENING WITH BSL 204	HARDENING WITH BSL 204	HARDENING WITH BSL 204	HARDENING WITH BSL 204	HARDENING WITH BSL 204	HARDENING WITH BSL 204	27 LAYERS OF KEVLAR FABRIC(788)
NUMBER OF SPECIMENS	2	1	2	2	1	1	2

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TABLE 9 - AMD-BA SANDWICH PLANE SPECIMEN

WITH HONEYCOMB CORE THICKNESS 7,7MM AND 2024 + 351 SKIN

MATERIAL : KEVLAR 49(R) SATIN 8 (BROCHIER 788)

RESIN EPOXY 145-5 (54%)

AMD-BA DESIGNATION	BZ404 REP.21	BZ404 REP.22	BZ404 REP.32	BZ404 REP.29	BZ404 REP.30	BZ404 REP.33
NUMBER OF FABRIC PLIES	6+3	6+3	6+3	6+3	6+3	3+3
ARRANGEMENT OF PLIES	AMD-BA	AMD-BA	AMD-BA	CEAT	CEAT	AMD-BA
HONEYCOMB CORE HEXCEL REF.	GLASS NP3/16 6.0	1/8.5056 .0015 6.1	1/8.5056 .0015 6.1	1/8.5056 .0015 6.1	GLASS NP3/16 6.0	GLASS NP3/16 6.0
THICKNESS OF THE SKIN	0.6MM	0.6MM	0.4MM	0.4MM	0.4MM	0.6MM
UPPER EDGING	HARDENING WITH BSL 204	HARDENING WITH BSL 204	HARDENING WITH BSL 204	27 LAYERS OF KEVLAR FABRIC 788	27 LAYERS OF KEVLAR FABRIC 788	27 LAYERS OF KEVLAR FABRIC 788
NUMBER OF SPECIMENS	4	3	1	1	2	2

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TABLE 10 - MECHANICAL CHARACTERISTICS OF THE FABRICS (TENSION)

MATERIAL		KEVLAR(R) 49							
FABRIC STYLE		SATIN 8				SATIN 4			
USED IN SPECIMEN		MONOLITHIC		SANDWICH		MONOLITHIC		SANDWICH	
DIRECTION		WARP	WEFT	WARP	WEFT	WARP	WEFT	WARP	WEFT
CEAT DESIGNATION		2025K04	2026K04	2279K06	2281K06	2039K05	2028K05	2280K07	2282K07
THICKNESS (MM)		1,21	1,21	1,16	1,14	1,05	1,01	0,97	0,95
KVF (VOLUMIC RATIO OF FIBER)		0,378	0,376	0,390	0,396	0,459	0,478	0,498	0,509
TENSILE STRENGTH R_R (MPA)	GROSS	400	479	490	538	433	408	509	464
	KEVLAR	1058	1274	1256	1358	943	854	1022	911
TENSILE MODULUS E (MPA)	GROSS	20400	24300	26100	28500	29100	28100	30500	31400
	KEVLAR	53958	64628	66923	71969	63390	58787	61245	61689
$W = 0.5R^2_R/E$ (J/M^3)*	GROSS	3,92 10^6	4,72 10^6	4,60 10^6	5,08 10^6	3,22 10^6	2,96 10^6	4,25 10^6	3,43 10^6
	KEVLAR	10,37 10^6	12,56 10^6	11,78 10^6	12,8 10^6	7,019 10^6	6,20 10^6	8,53 10^6	6,74 10^6

* THE TENSILE TEST CURVES ARE LINEAR UP TO FAILURE.

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TABLE 10 - MECHANICAL CHARACTERISTICS OF THE FABRICS (TENSION)

(SUITE)

MATERIAL		KEVLAR(R)29			
FABRIC STYLE		SATIN 8		SATIN 4	
USED IN SPECIMEN		MONOLITHIC		MONOLITHIC	
DIRECTION		WARP	WEFT	WARP	WEFT
CEAT DESIGNATION		2416K09	2417K09	2411K08	2412K08
THICKNESS (MM)		0,965	0,91	0,936	0,865
KVF (VOLUMIC RATIO OF FIBER)		0,472	0,502	0,487	0,527
TENSILE STRENGTH R_R (MPA)	GROSS	609	615	548	445
	KEVLAR	1290	1225	1125	844
TENSILE MODULUS E (MPA)	GROSS	24600	25200	23400	20500
	KEVLAR	52119	50199	48049	38900
$W = 0.5R^2_R/E$ (J/M^3)*	GROSS	7,54 10^6	7,50 10^6	6,42 10^6	4,83 10^6
	KEVLAR	10,37 10^6	12,56 10^6	11,78 10^6	12,8 10^6

* THE TENSILE TEST CURVES ARE LINEAR UP TO FAILURE.

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TABLE 11 - NUMBER OF SHOTS

SHOOTING CONDITIONS	NORMAL IMPACT		OBLIQUE IMPACT	
DESIGNATION OF SPECIMEN	NUMBER OF SHOTS	SPECIMENS USED	NUMBER OF SHOTS	SPECIMENS USED
SQUARE PLATES MONOLITHIC	38	19/22	15	7
CEAT SANDWICH SQUARE PLATES(1 LAYER HONEYCOMB)	29	16/16		
CEAT SANDWICH SQUARE PLATES(2 LAYERS HONEYCOMB)	12	9/12		
SANDWICH CURVED SPECIMEN 1 LAYER HONEYCOMB(BZ3101-2-3)	7	6/6		
-IDEM- BZ310 REP.1 BZ404 REP.11-14-15	7	5/5	4	3/3
AEROSPATIALE LEADING EDGES	3	3		
AMD-BA SQUARE PLATES MONOLITHIC (KEVLAR 49)	20	10/10		
AMD-BA AND CEAT SQUARE PLATES MONOLITHIC(KEVLAR 29)	9	5/5		
AMD-BA RECTANGULAR PLATES MONOLITHIC BZ404 (TABLE 7)			9	9/10
AMD-BA SANDWICH PLANE PLATES BZ404 (TABLE 8)			10	10/11
AMD-BA SANDWICH PLANE PLATES WITH 2024 SKIN BZ404(TABLE 9)			12	12/13

TABLE 12

FAILURE PATTERN

W_O = INITIAL BIRD KINETIC ENERGY

W_P = BIRD KINETIC ENERGY OF PENETRATION (LIMIT)

W_A = KINETIC ENERGY ABSORBED

FAILURE PATTERN	STAR				BOOK PAGE			
SPECIMEN DESIGNATION	TEST NUMBER	FIGURE	W_O/W_P	W_A/W_P	TEST NUMBER	FIGURE	W_O/W_P	W_A/W_P
MONOLITHIC	37	25	1,135	0,527	40	25	1,068	0,868
SANDWICH ONE LAYER OF HONEYCOMB	54	26	1,468	0,641	68	26	1,082	0,908
SANDWICH TWO LAYERS OF HONEYCOMB	157	27	2,096	0,489	159	27	1,059	0,937
RADOME TYPE					100	28	1,007	0,895
RADOME TYPE					96	28	1,193	0,792
LEADING EDGE TYPE	90	29	1,202	0,519				
AEROSPATIALE LEADING EDGES.	93 94	29 29	1,882 1,673	0,464 0,524				

F I G U R E S

FIGURE 1

Falcon 900: Composite materials

Total weight of composite structure: 1000 lb

Aramide/epoxy Graphite/epoxy

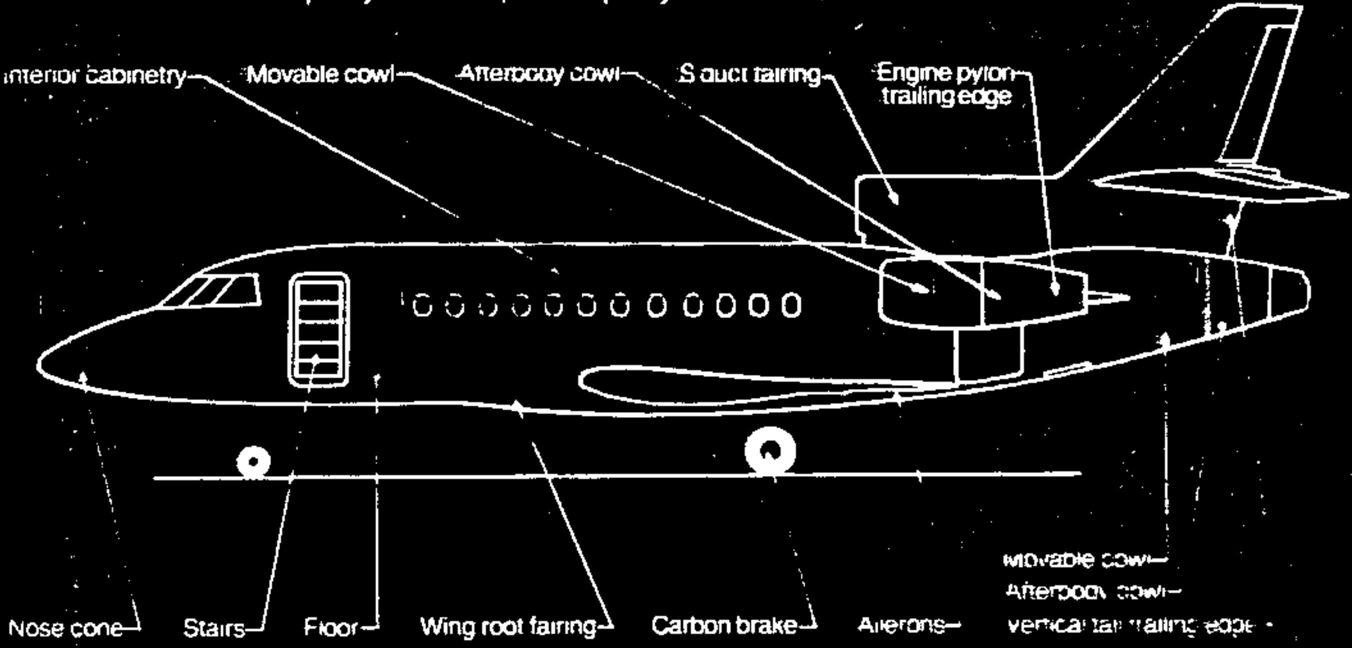


FIGURE 2

ATR - 42 COMPOSITE STRUCTURES

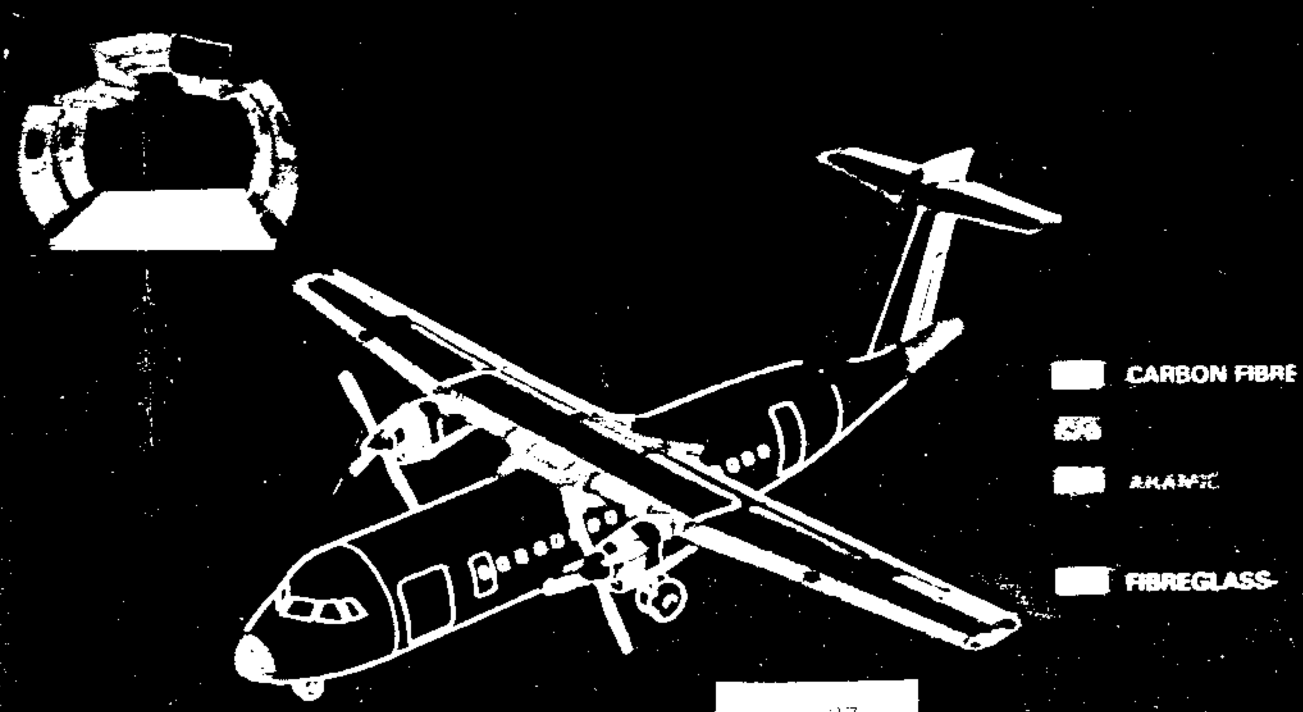
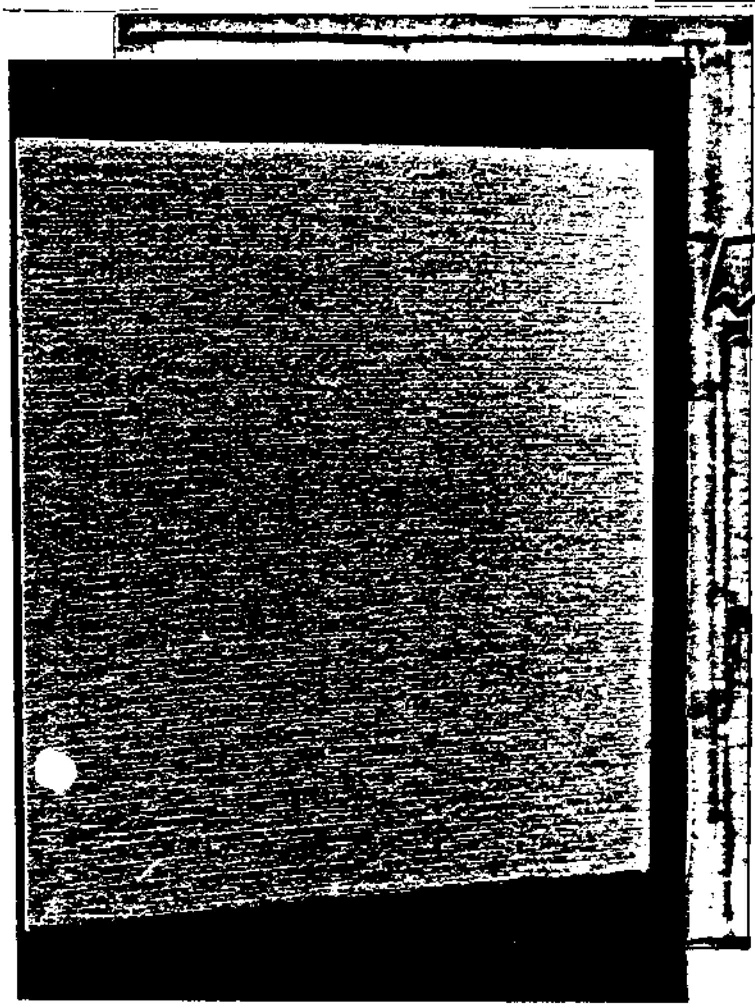


FIGURE 3



MONOLITHIC PLANE SPECIMEN

The arrow on the forward face indicates the direction of the warp of the first ply of fabric

FIGURE 4

SANDWICH PLANE SPECIMEN

One layer of honeycomb

THICKNESS OF THE HONEYCOMB CORE

t = 7,5 mm

t = 20 mm

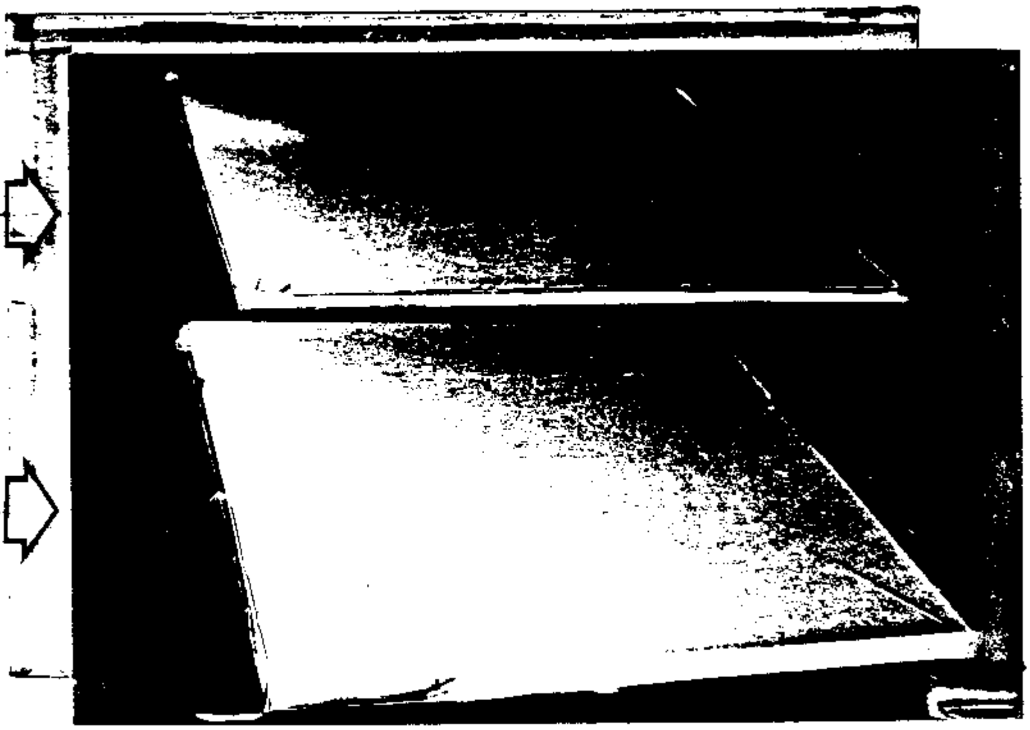


FIGURE 5

CEAT PLANE PLATES SANDWICH

WITH TWO LAYERS OF NOMEX® HONEYCOMB CORE

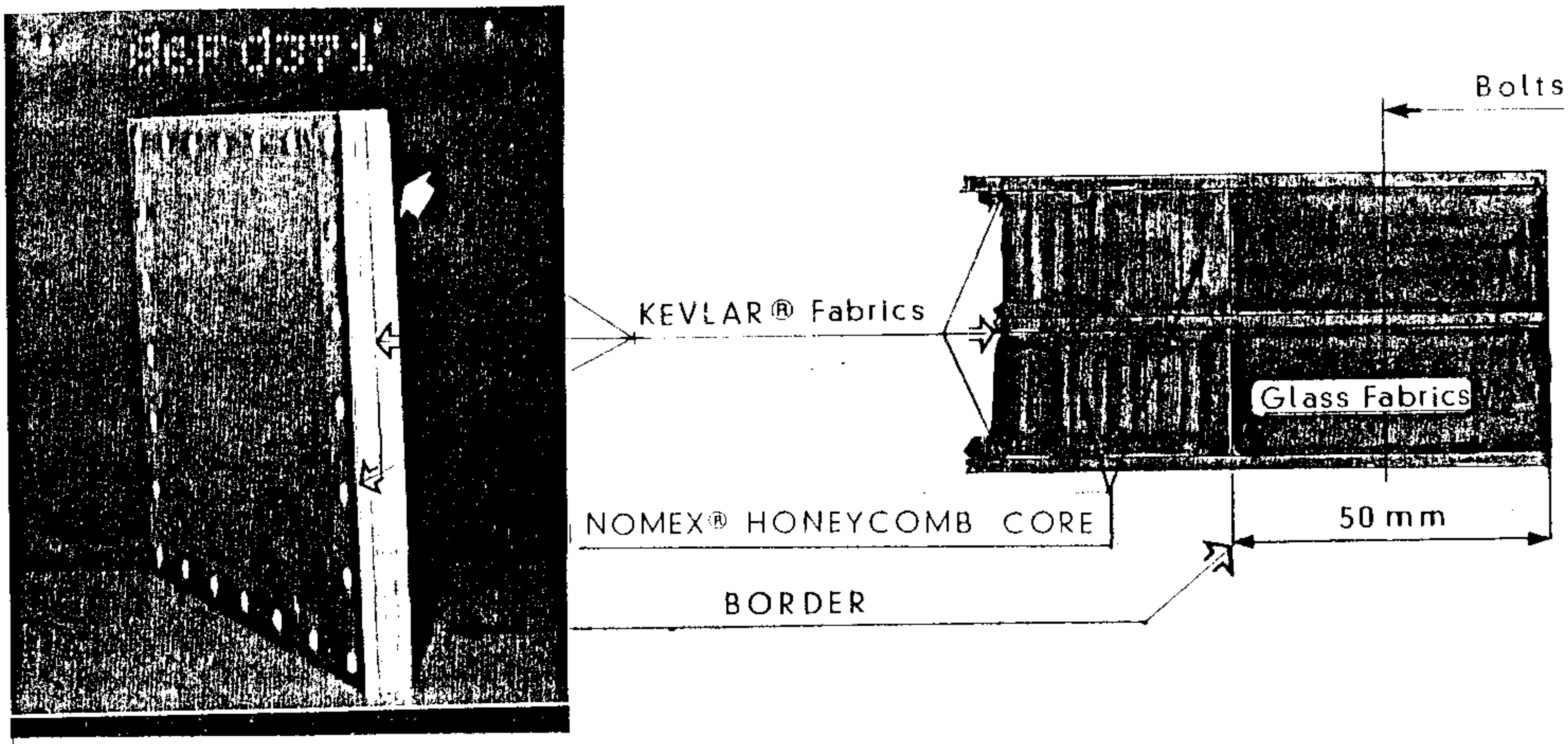


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FIGURE 6

SANDWICH CURVED SPECIMEN

One layer of honeycomb

Representative of the leading edges

SMALL RADIUS

OF CURVATURE

R = 100 mm

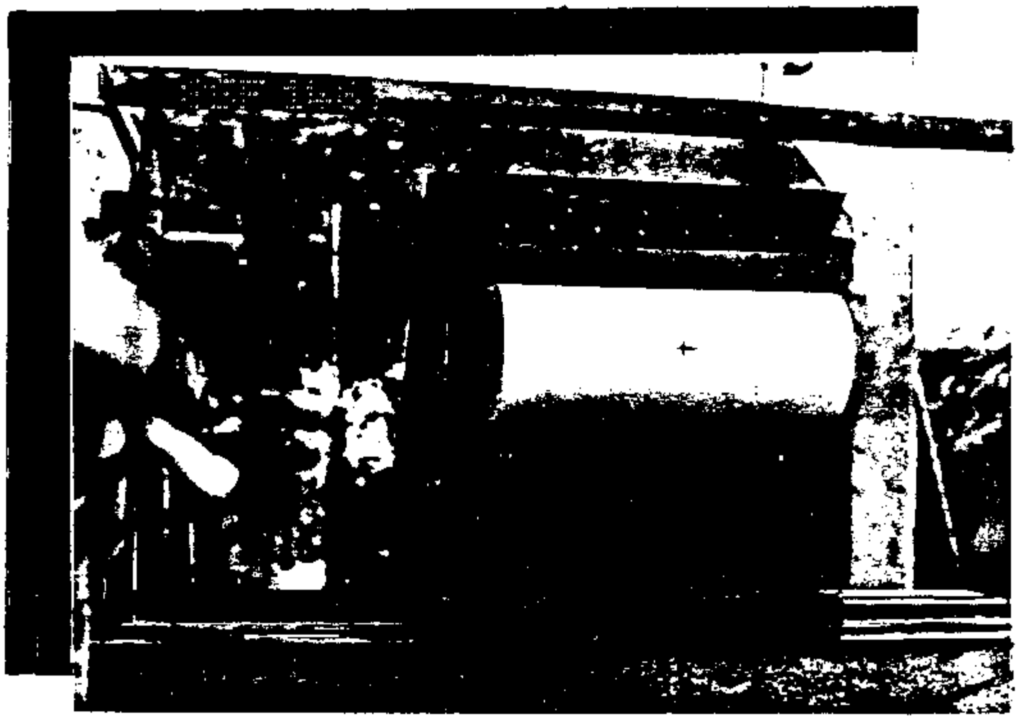


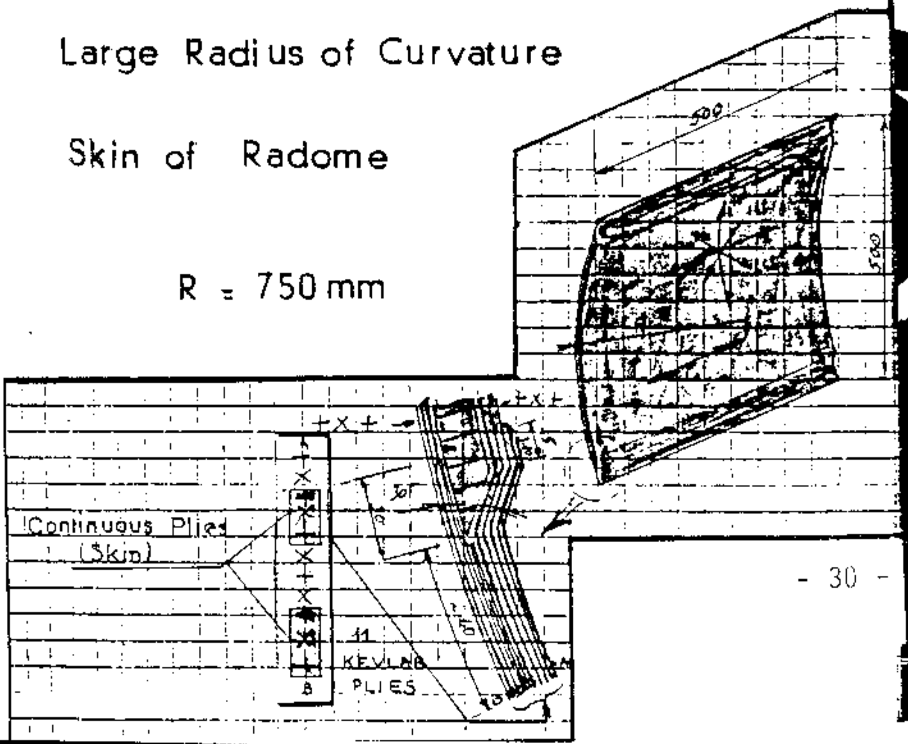
FIGURE 7

SANDWICH CURVED SPECIMENS (ONE LAYER OF HONEYCOMB)

Large Radius of Curvature

Skin of Radome

R = 750 mm



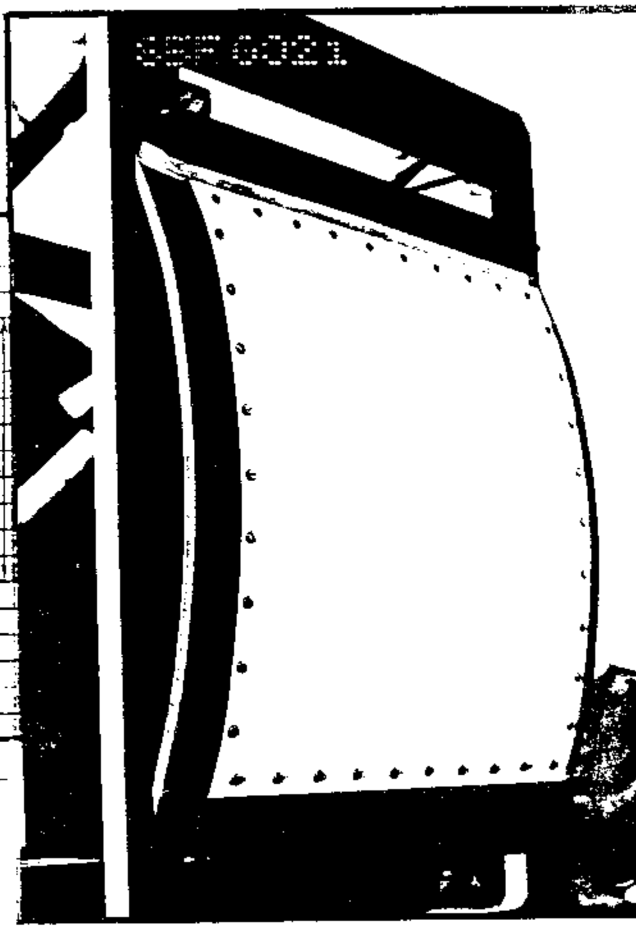
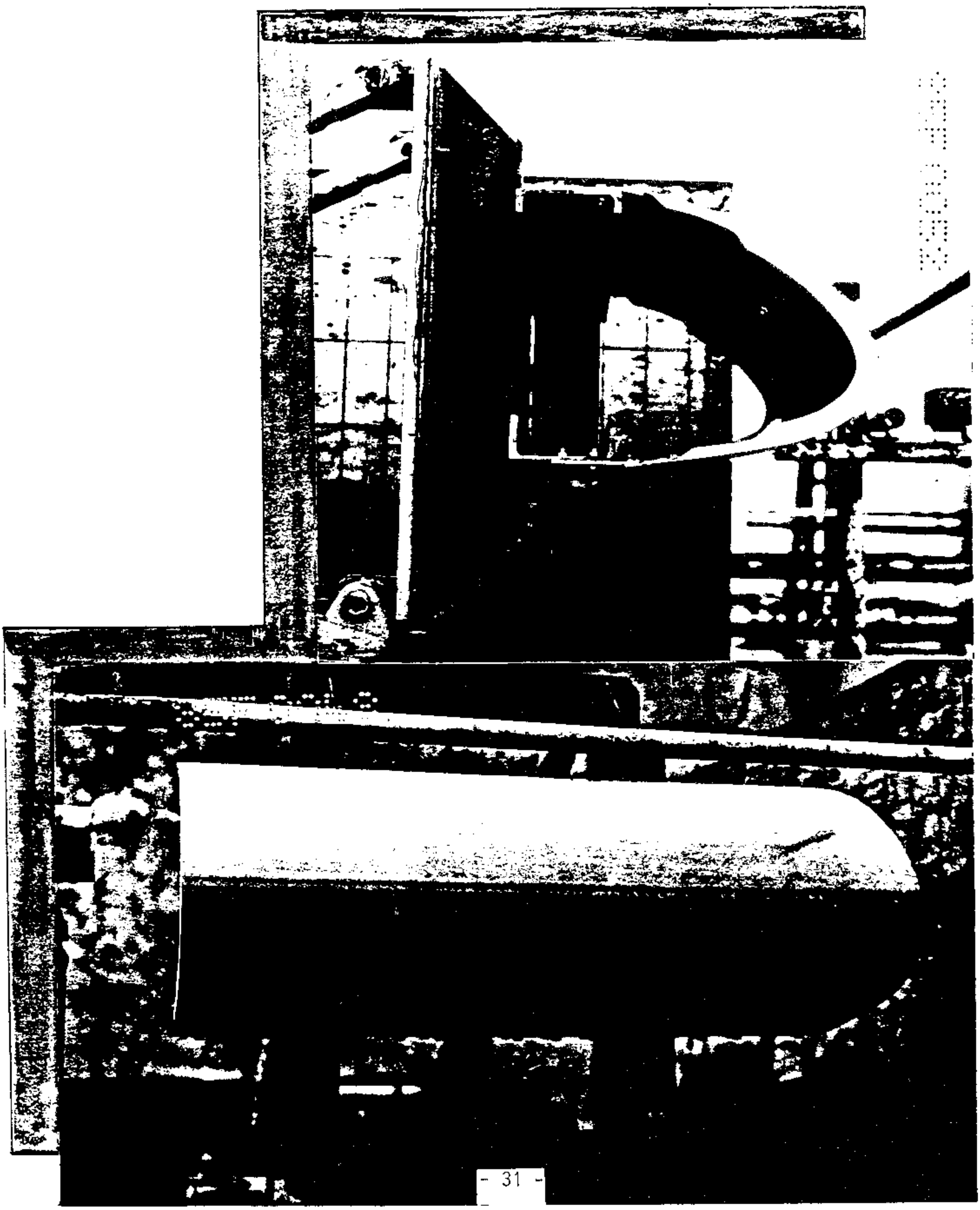


FIGURE 8

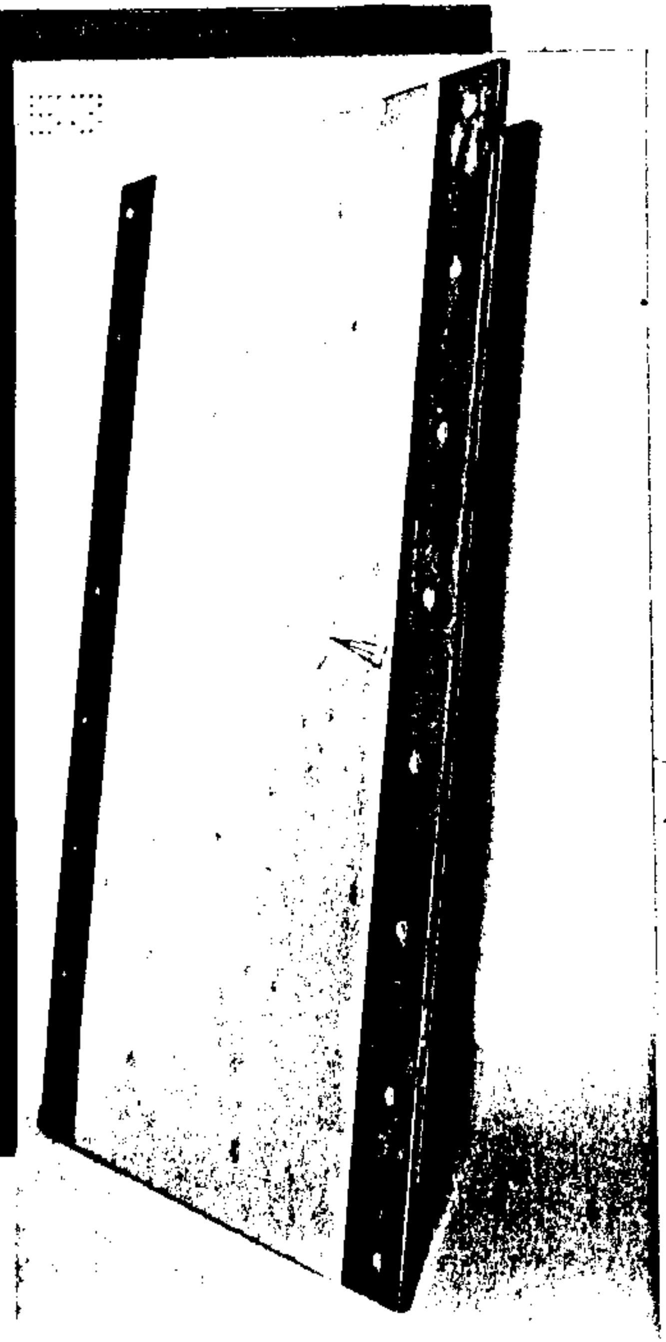
AEROSPATIALE LEADING EDGES

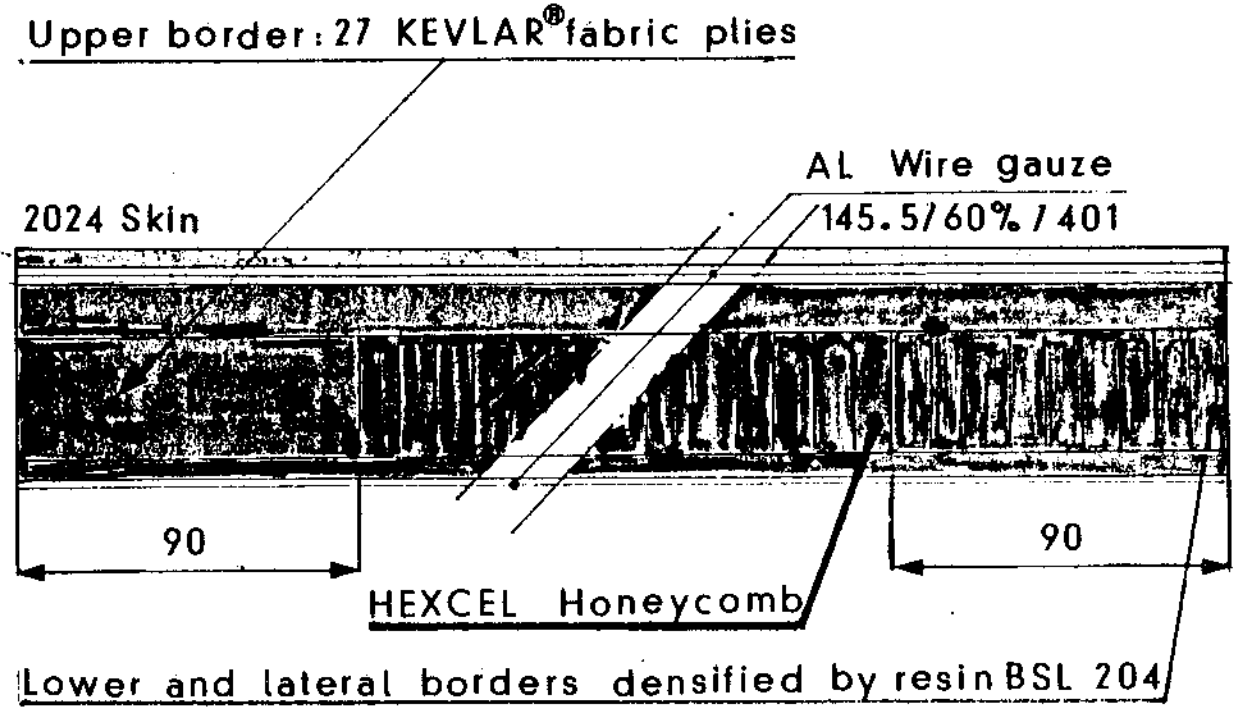


F I G U R E 9

AMD-BA PLANE PLATES SANDWICH

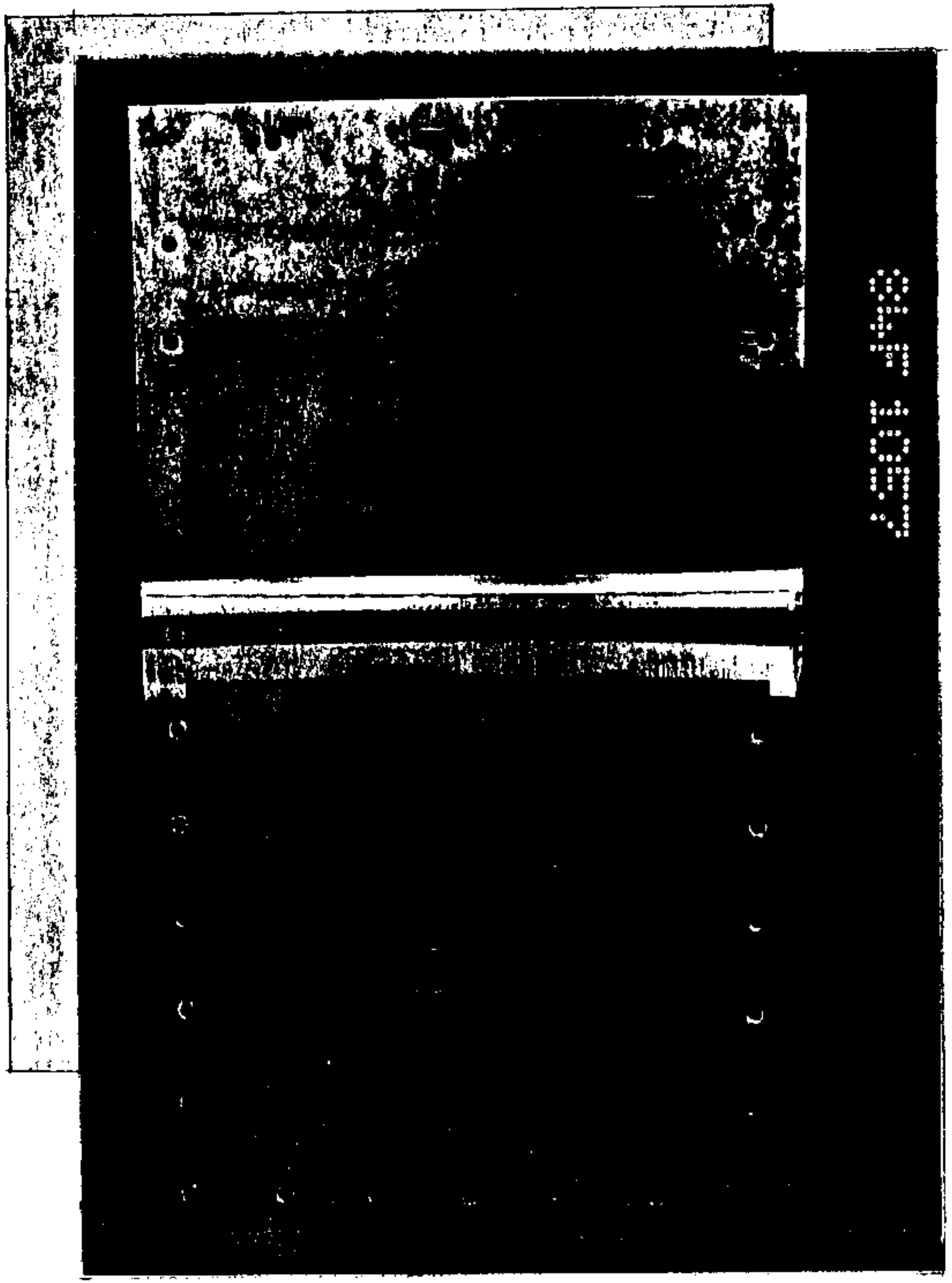
WITH 2024 SKIN





REGISTERED TRADE MARK

FIGURE 10

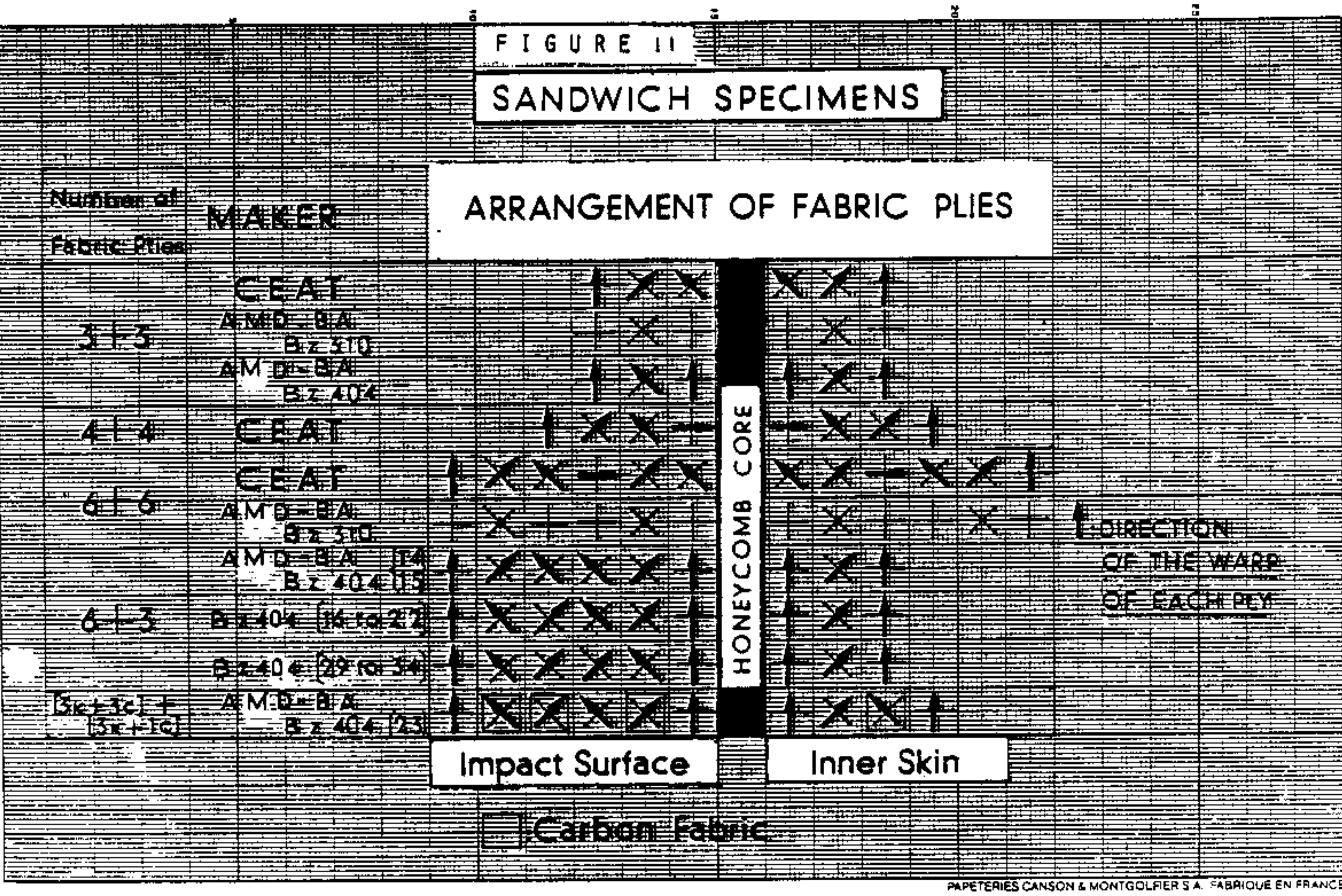


CEAT

MONOLITHIC PLANE PLATES

Specimen Modification For Oblique Impact

Bonding of a Duralumin sheet at the top edge of the composite plate.



CE DOCUMENT EST LA PROPRIÉTÉ DES AVIONS MARCEL DASSAULT - BREGUET AVIATION. IL NE PEUT ÊTRE UTILISÉ, REPRODUIT OU COMMUNIQUÉ SANS LEUR AUTORISATION

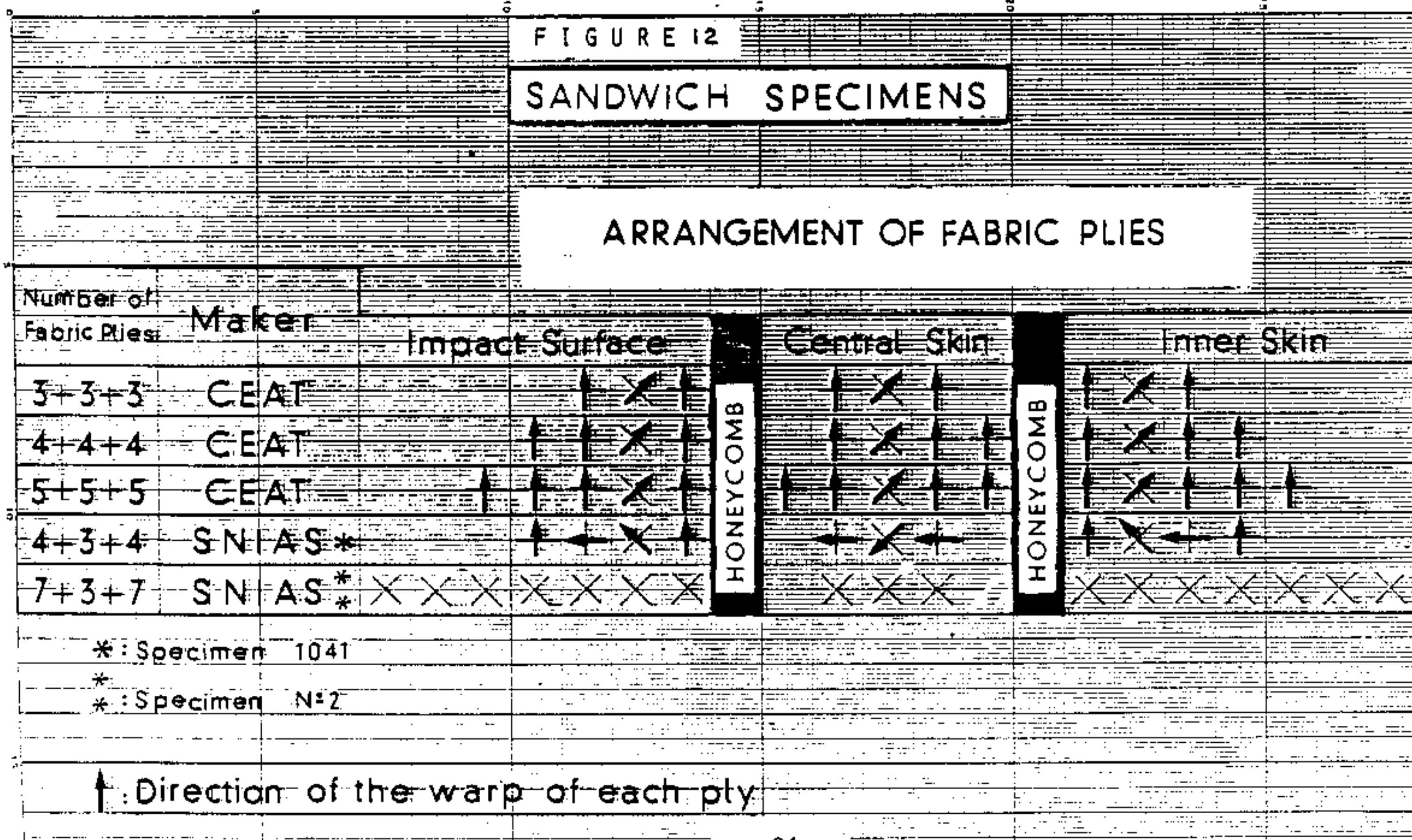


FIGURE 13

MONOLITHIC PLANE PLATES

ARRANGEMENT OF FABRIC PLIES

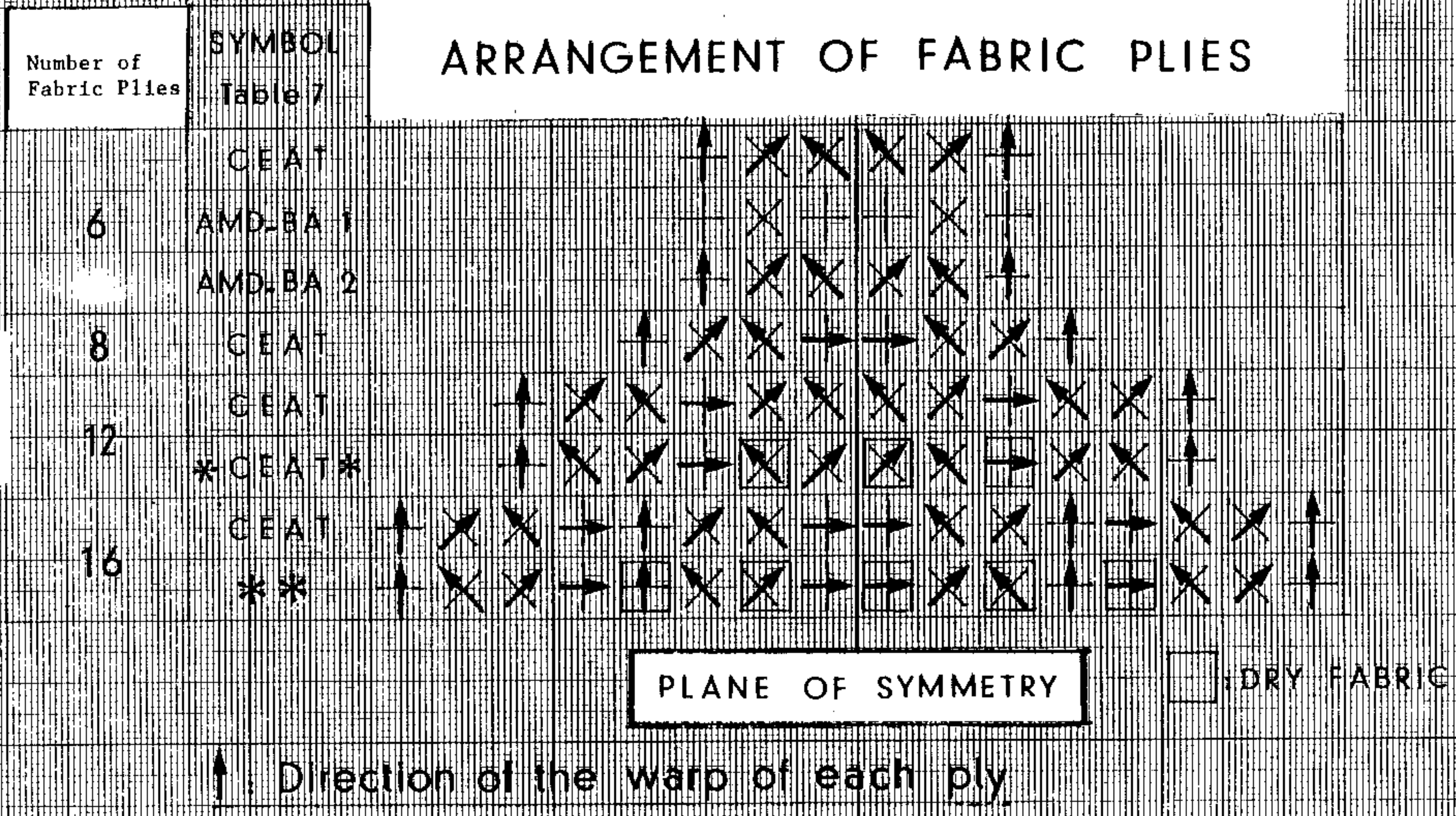


FIGURE 14

CEAT IMPACT TEST FACILITY

Air Pressurized Guns

Ø:300 mm

Ø:150 mm

FIGURE 15

FRAME FOR SQUARE PLATES

IN NORMAL IMPACT

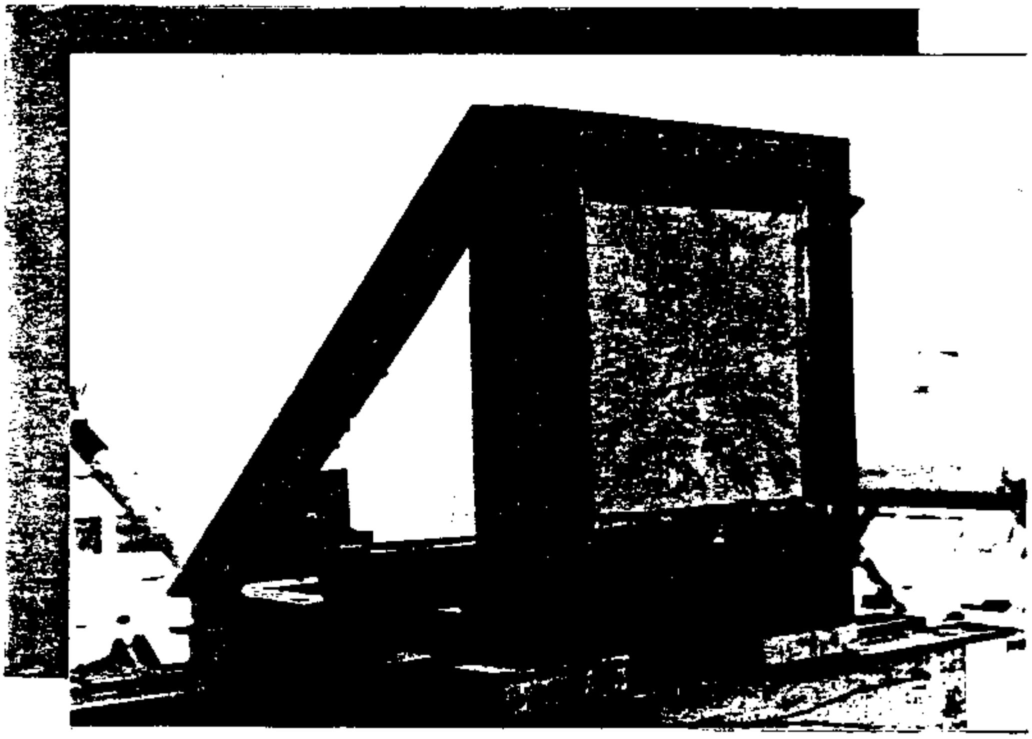
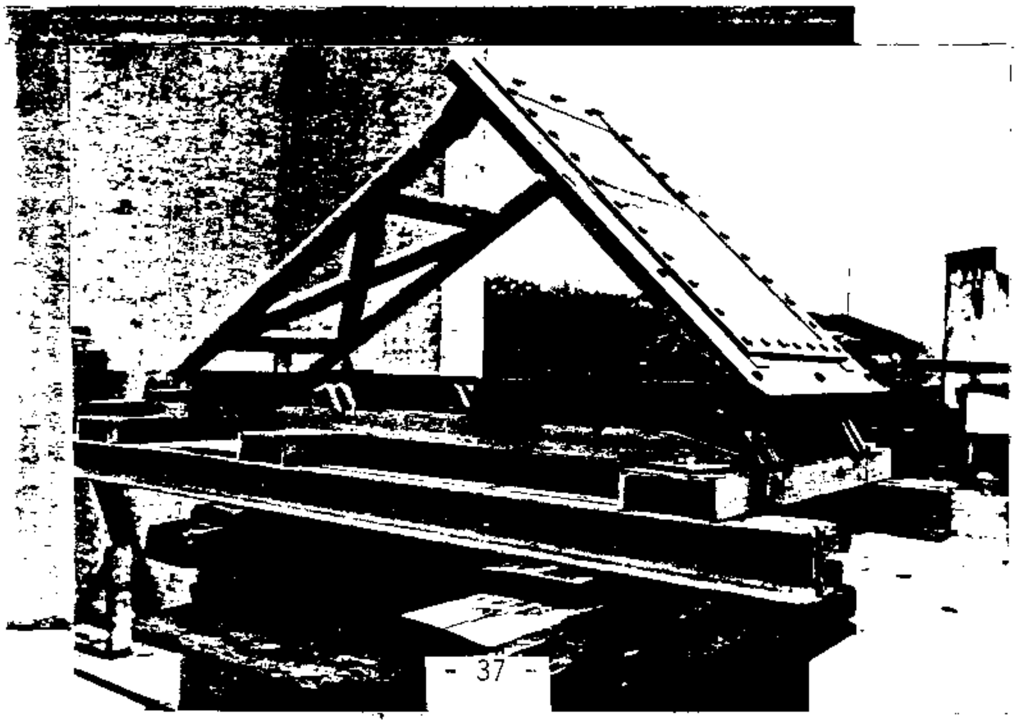


FIGURE 16

INCLINABLE SUPPORT

FOR OBLIQUE IMPACTS



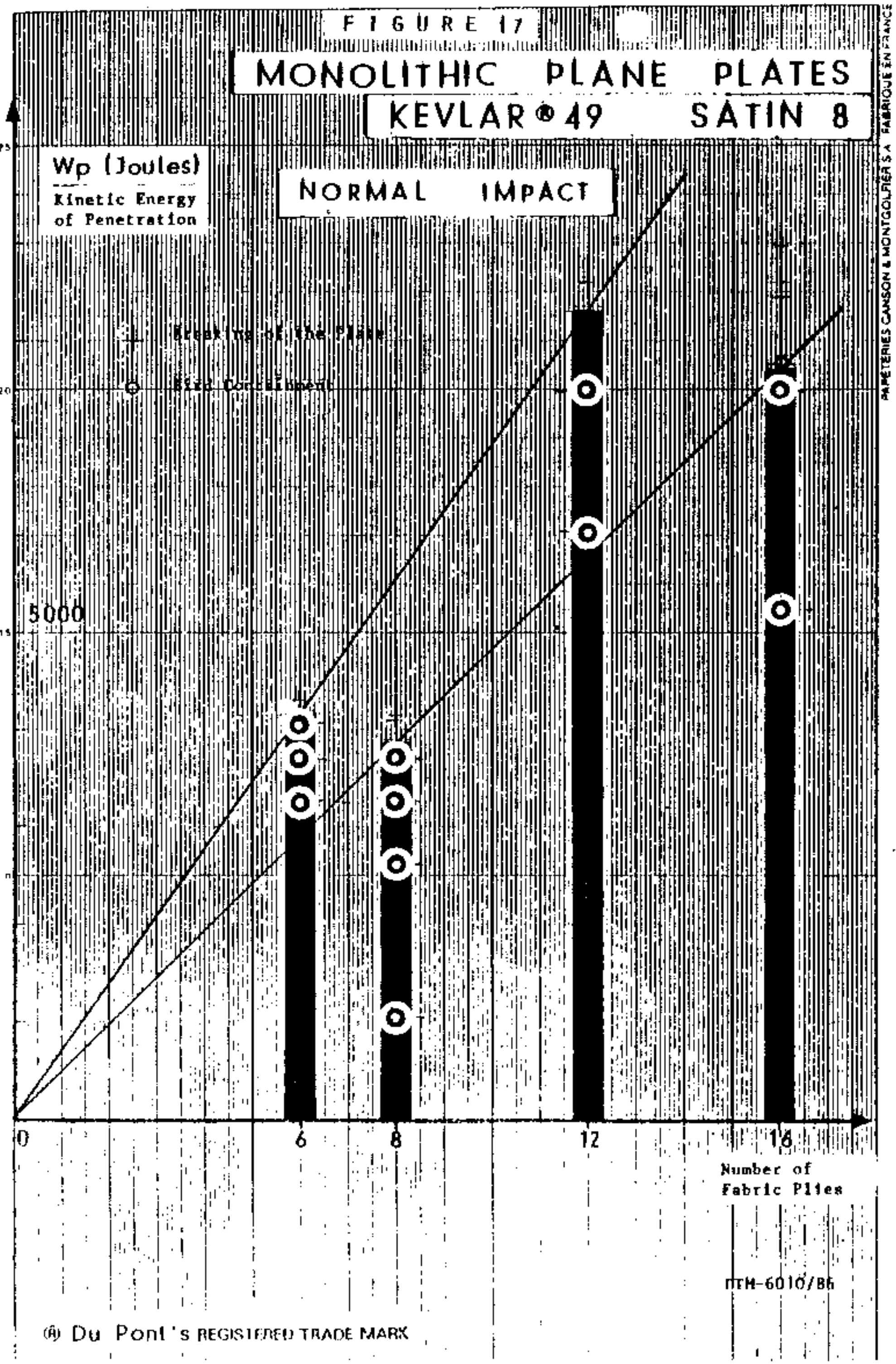


FIGURE 17
MONOLITHIC PLANE PLATES
KEVLAR ® 49 SATIN 8
Wp (Joules)
Kinetic Energy of Penetration
NORMAL IMPACT
5000
0
6
8
12
16
Number of Fabric Plies
DTN-6010/86
® Du Pont's REGISTERED TRADE MARK

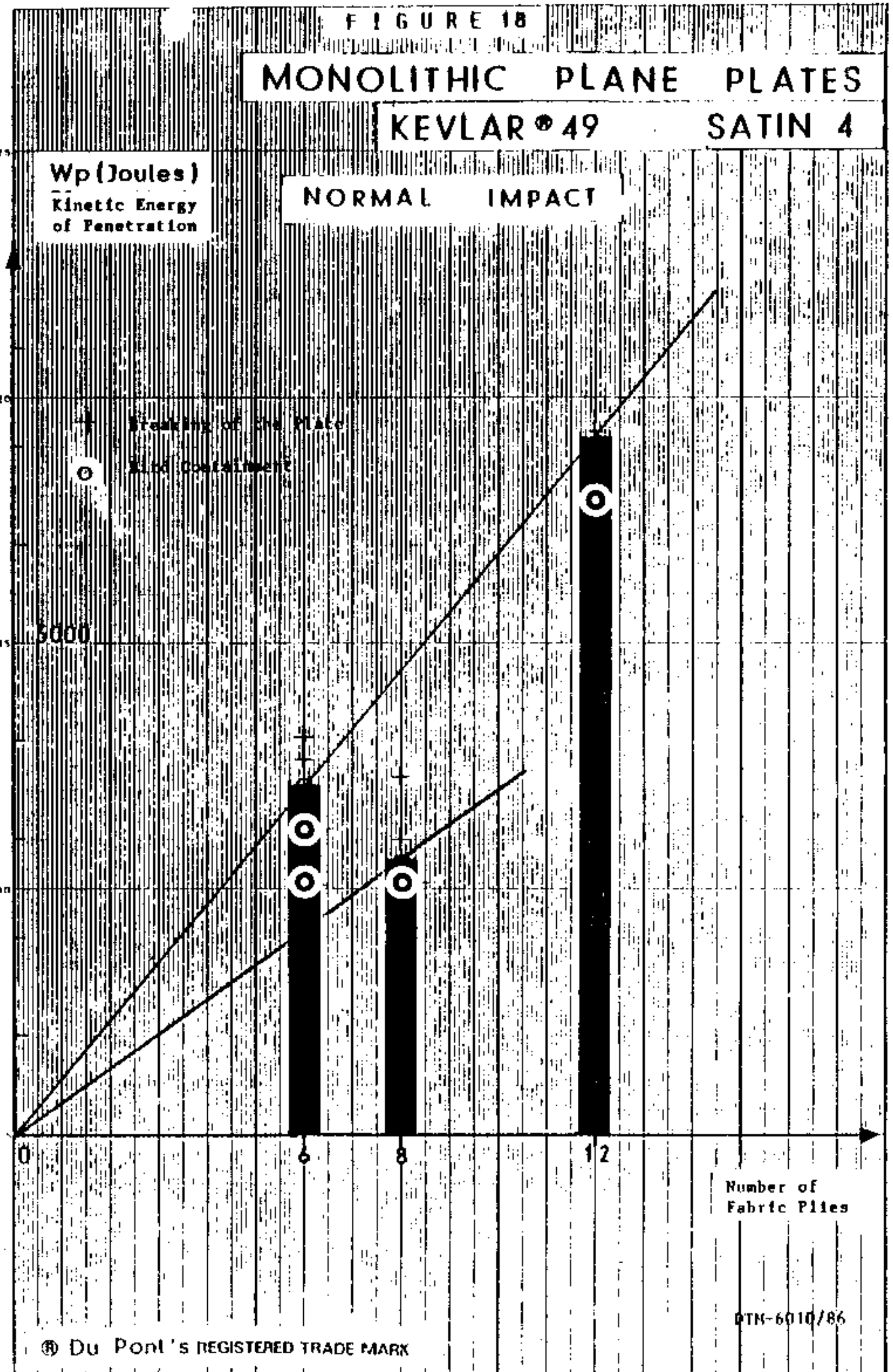
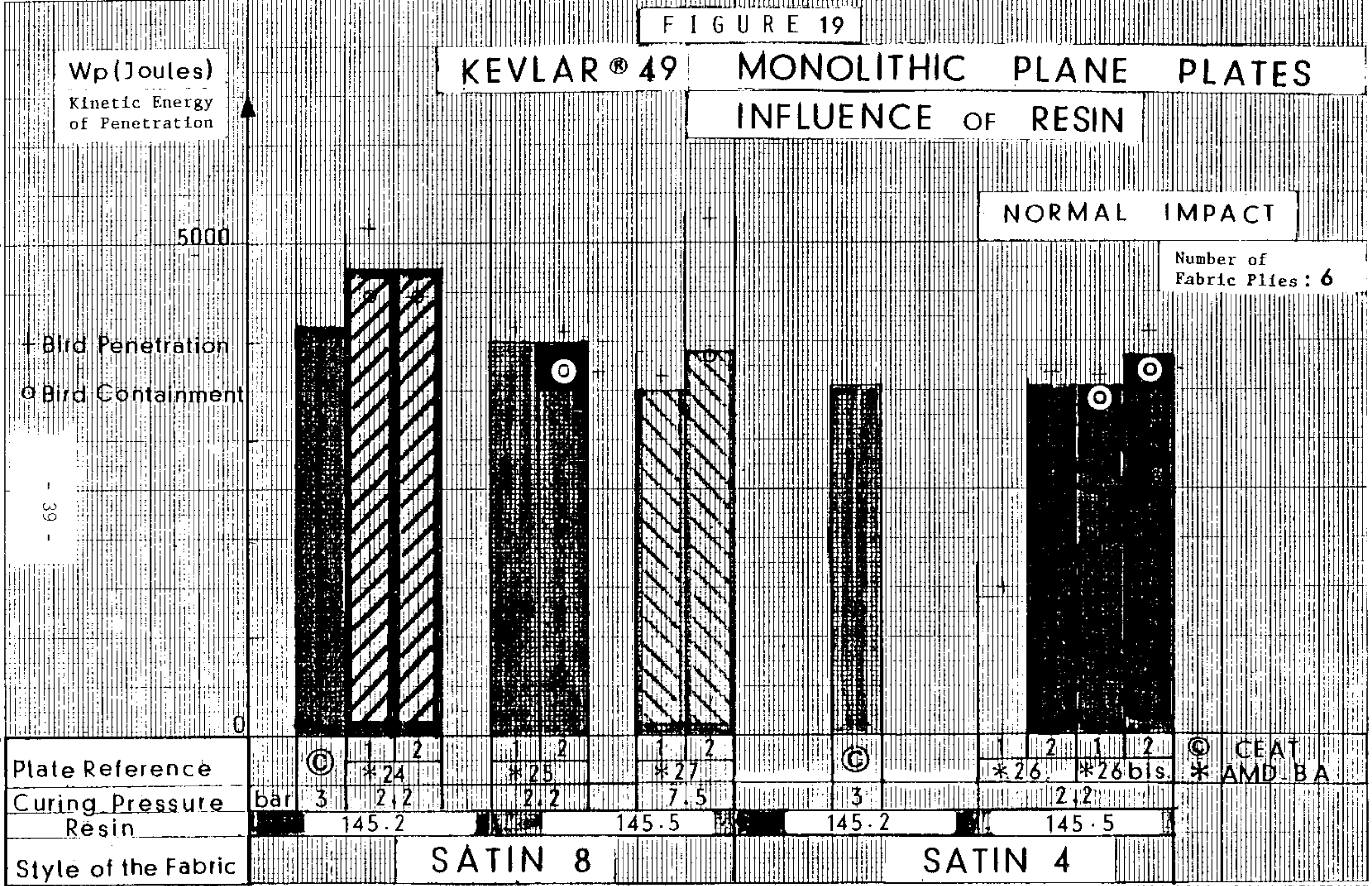


FIGURE 18
MONOLITHIC PLANE PLATES
KEVLAR ® 49 SATIN 4
Wp (Joules)
Kinetic Energy of Penetration
NORMAL IMPACT
5000
0
6
8
12
Number of Fabric Plies
DTN-6010/86
® Du Pont's REGISTERED TRADE MARK

FIGURE 19



® Du Pont's REGISTERED TRADE MARK

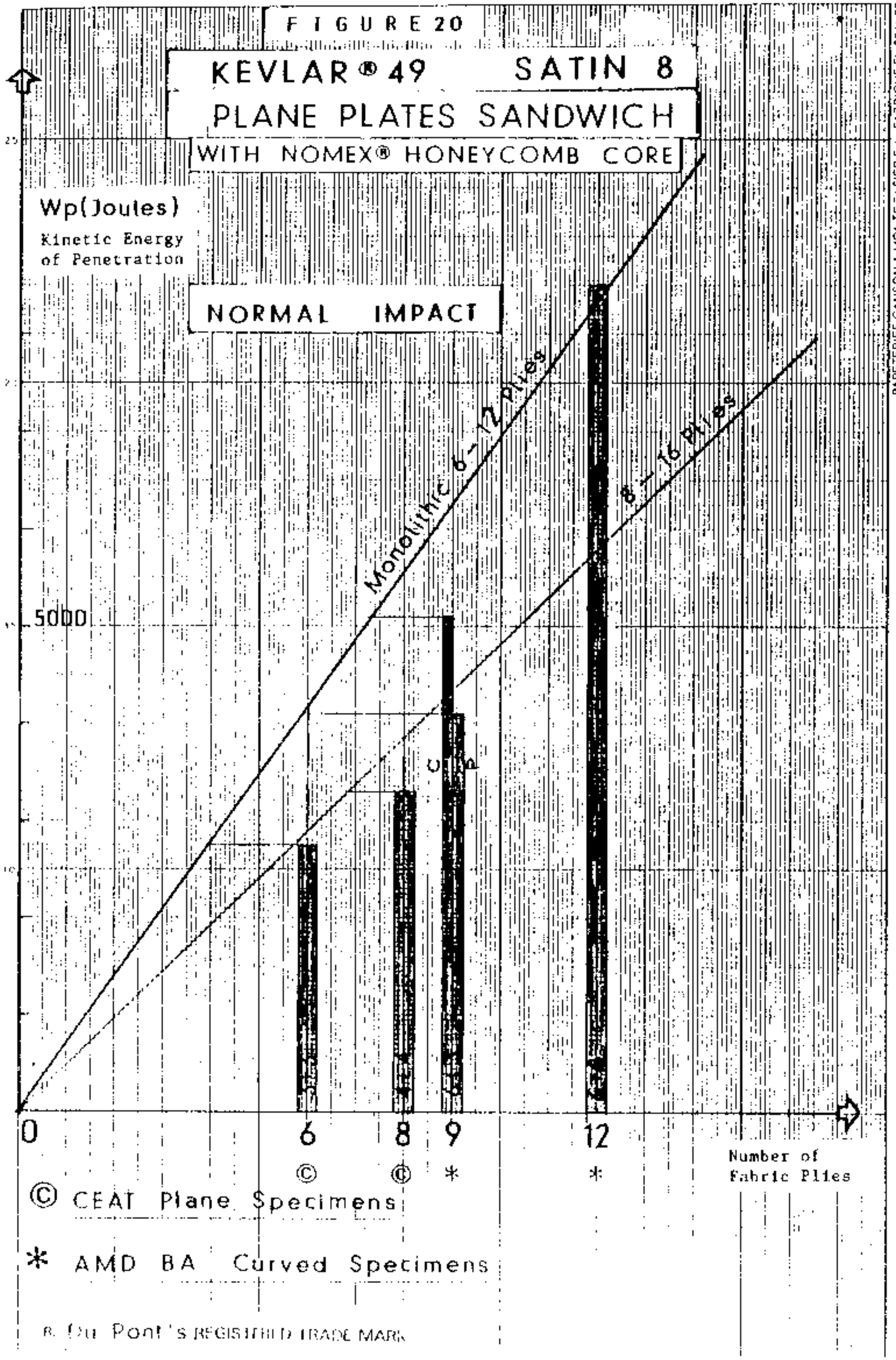


FIGURE 20
KEVLAR® 49 SATIN 8
PLANE PLATES SANDWICH
WITH NOMEX® HONEYCOMB CORE
Wp(Joules)
Kinetic Energy of Penetration
NORMAL IMPACT
5000
Monolithic 6 – 12 Plies
8 – 16 Plies
0
6
8
9
12
Number of Fabric Plies
© CEAT Plane Specimens
* AMD BA Curved Specimens
® Du Pont's REGISTERED TRADE MARK

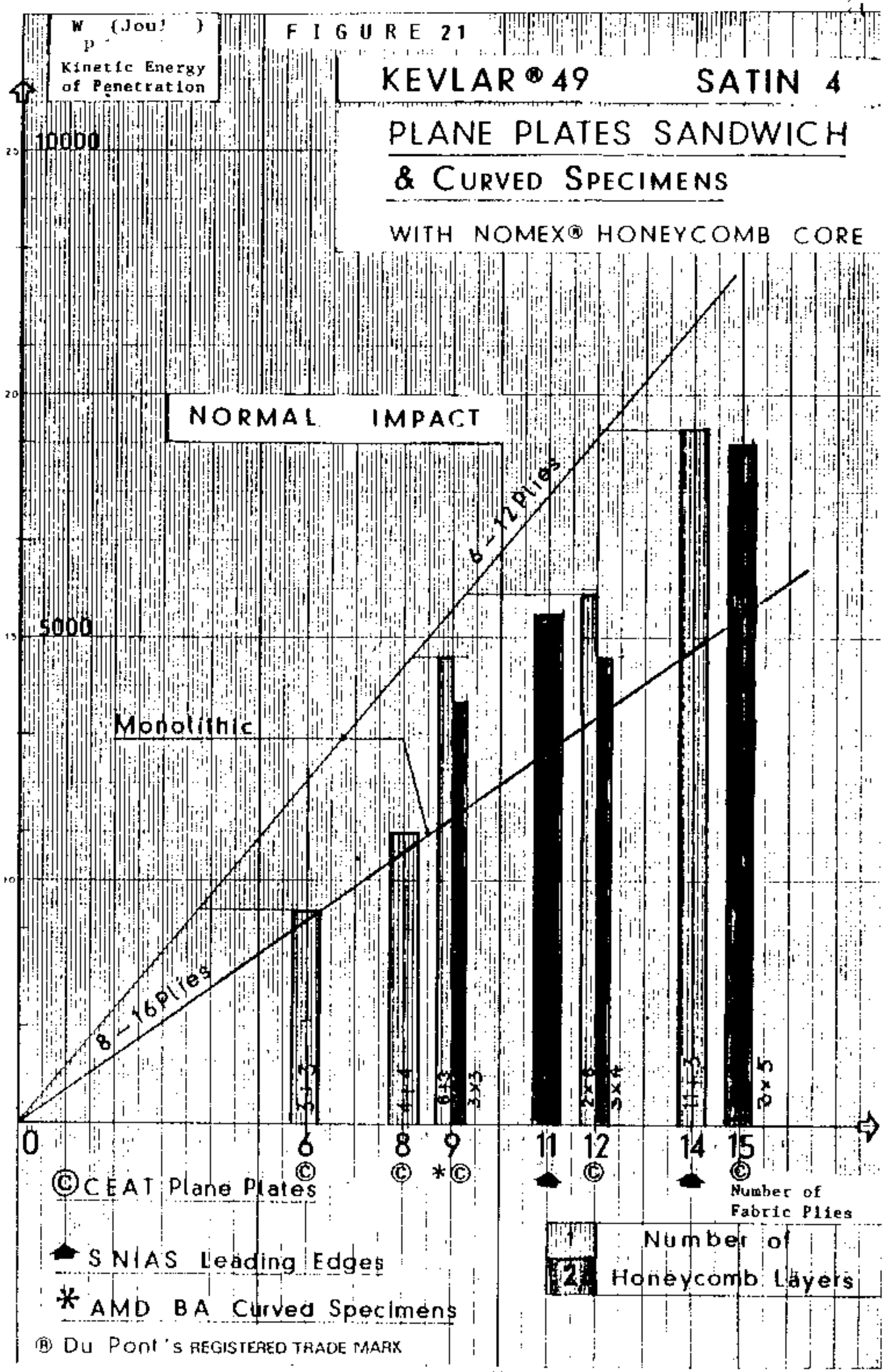


FIGURE 21
KEVLAR® 49 SATIN 4
PLANE PLATES SANDWICH
& CURVED SPECIMENS
WITH NOMEX® HONEYCOMB CORE
Kinetic Energy of Penetration
10000
5000
NORMAL IMPACT
6 – 12 Plies
Monolithic
8 – 16 Plies
0
6
8
9
11
12
14
15
Number of Fabric Plies
©CEAT Plane Plates
SNIAS Leading Edges
* AMD BA Curved Specimens
Number of Honeycomb Layers
® Du Pont's REGISTERED TRADE MARK

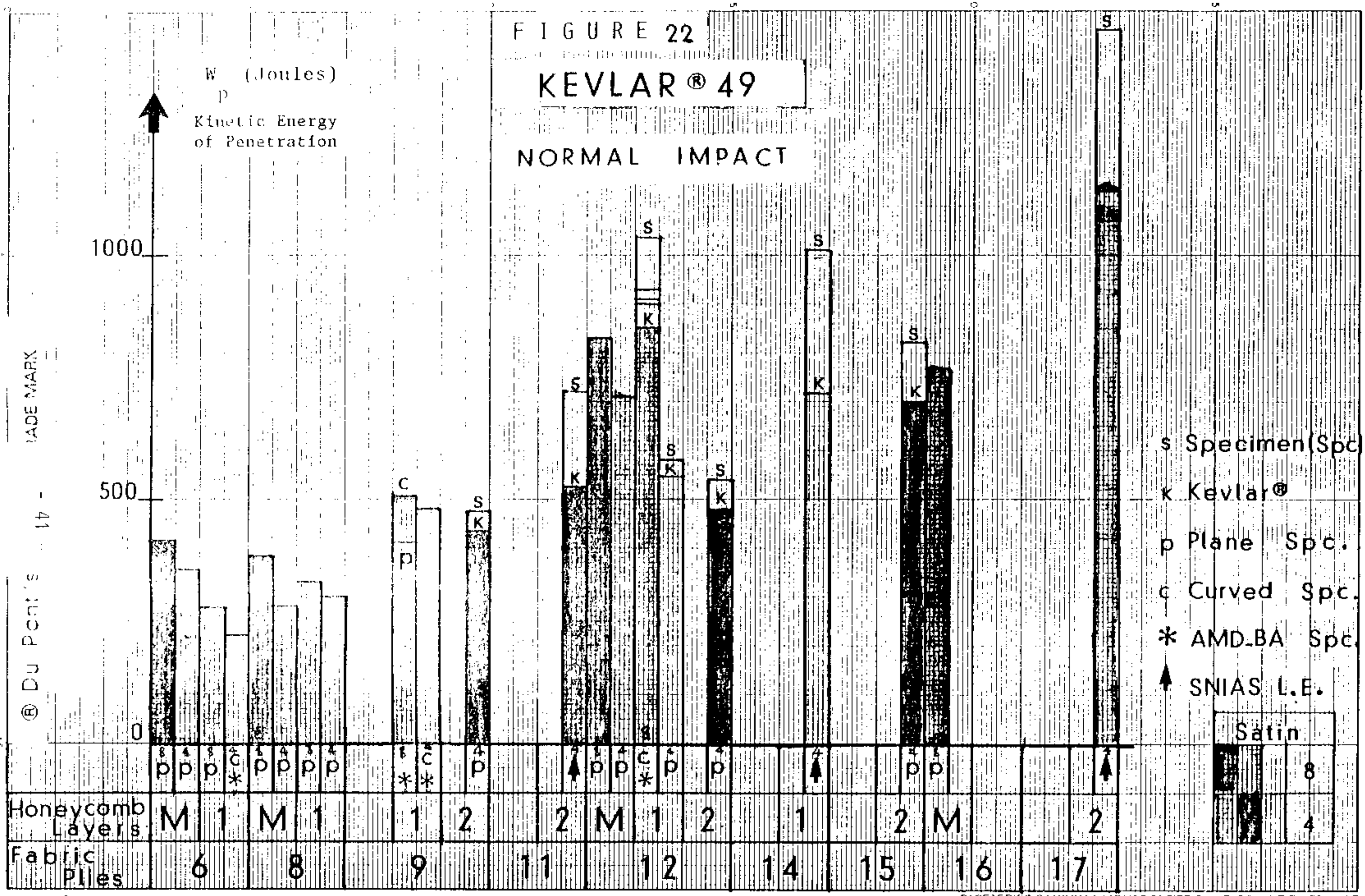


FIGURE 22
KEVLAR ® 49
NORMAL IMPACT
W p (Joules)
Kinetic Energy of Penetration
1000
500
0
s Specimen(Spc)
k Kevlar®
p Plane Spc.
c Curved Spc.
* AMD-BA Spc.
SNIAS L.E.
Satin
8
4
Honeycomb Layers
Fabric Plies
6
8
9
11
12
14
15
16
17

FIGURE 23

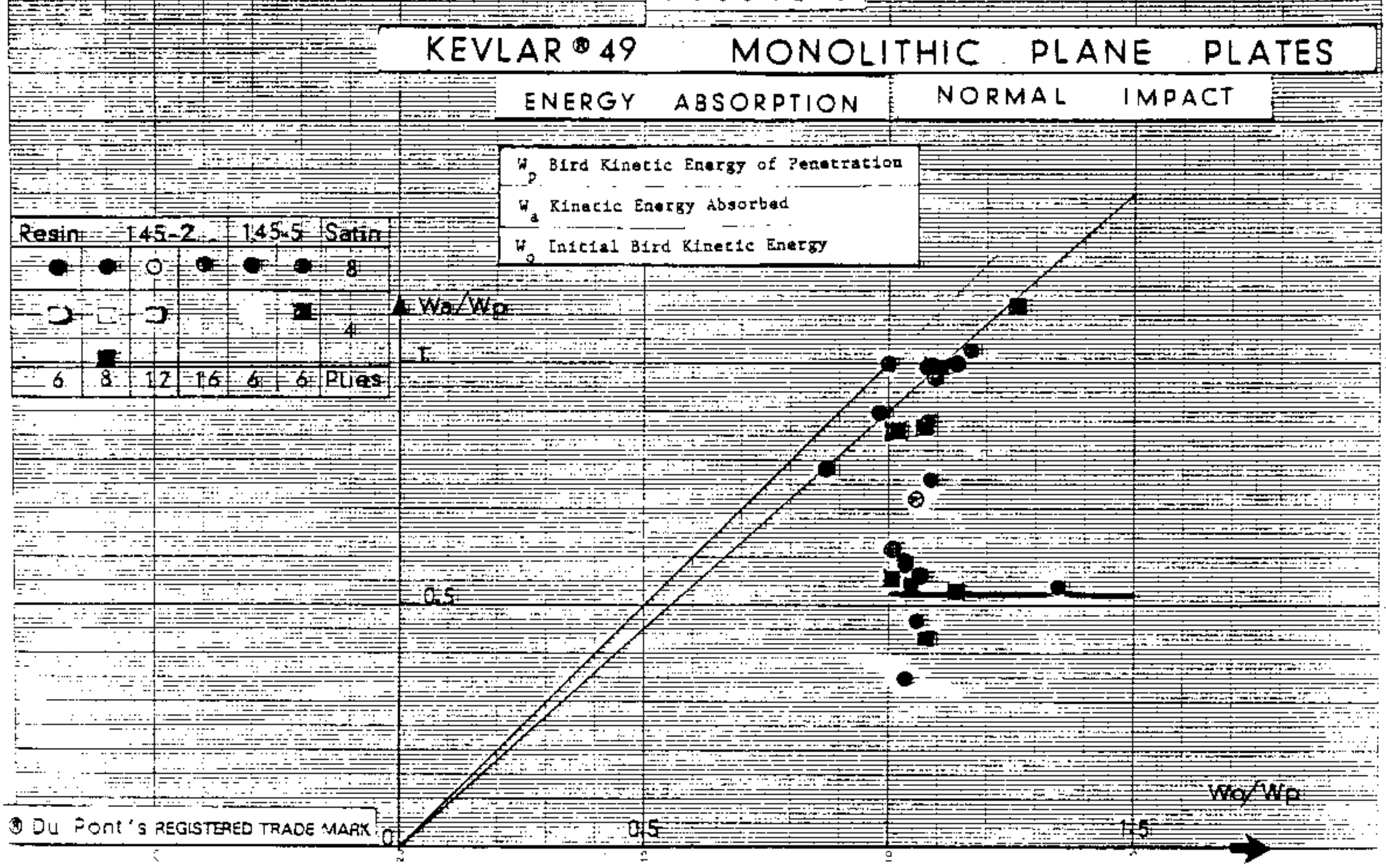


FIGURE 24

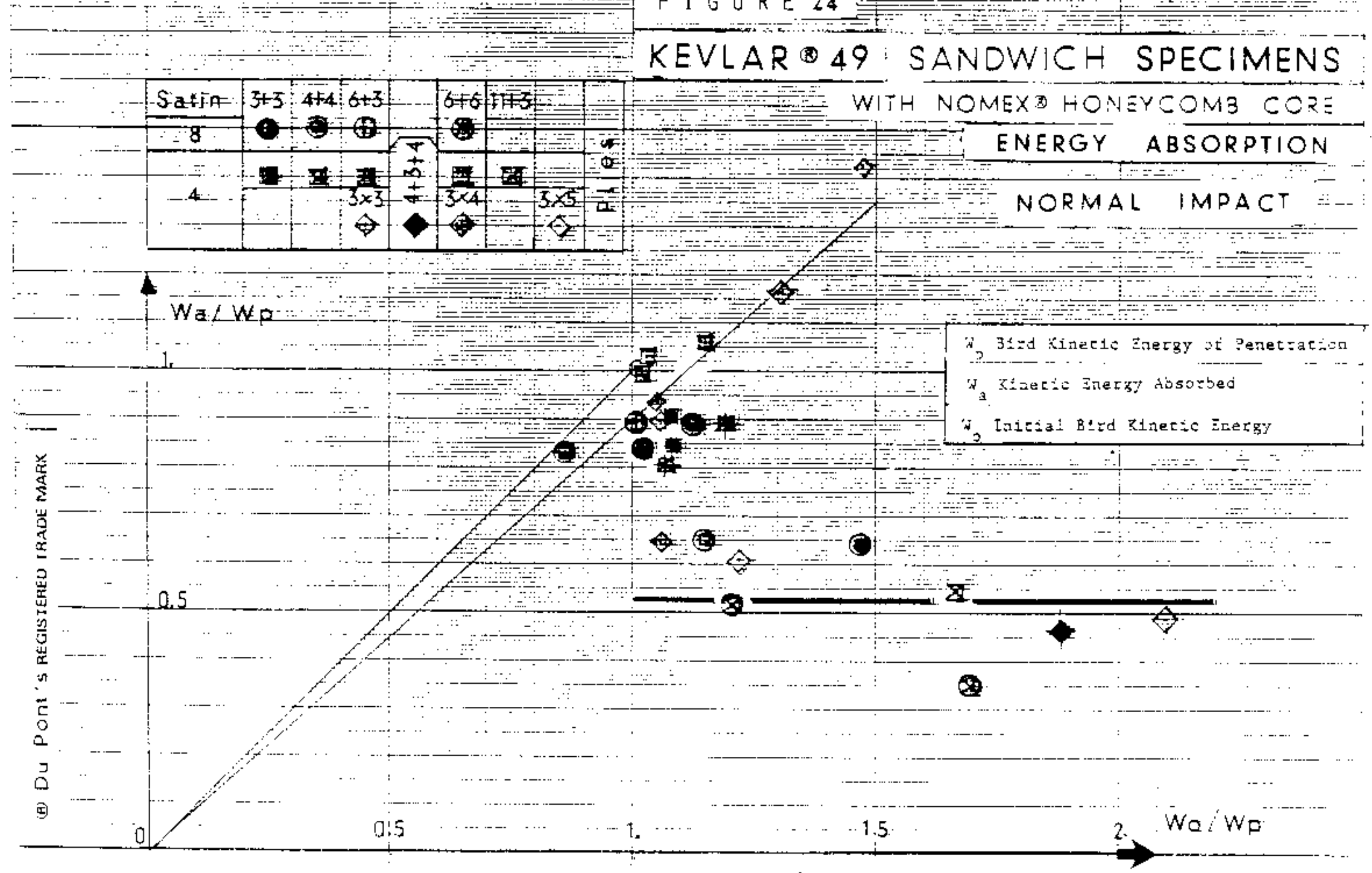


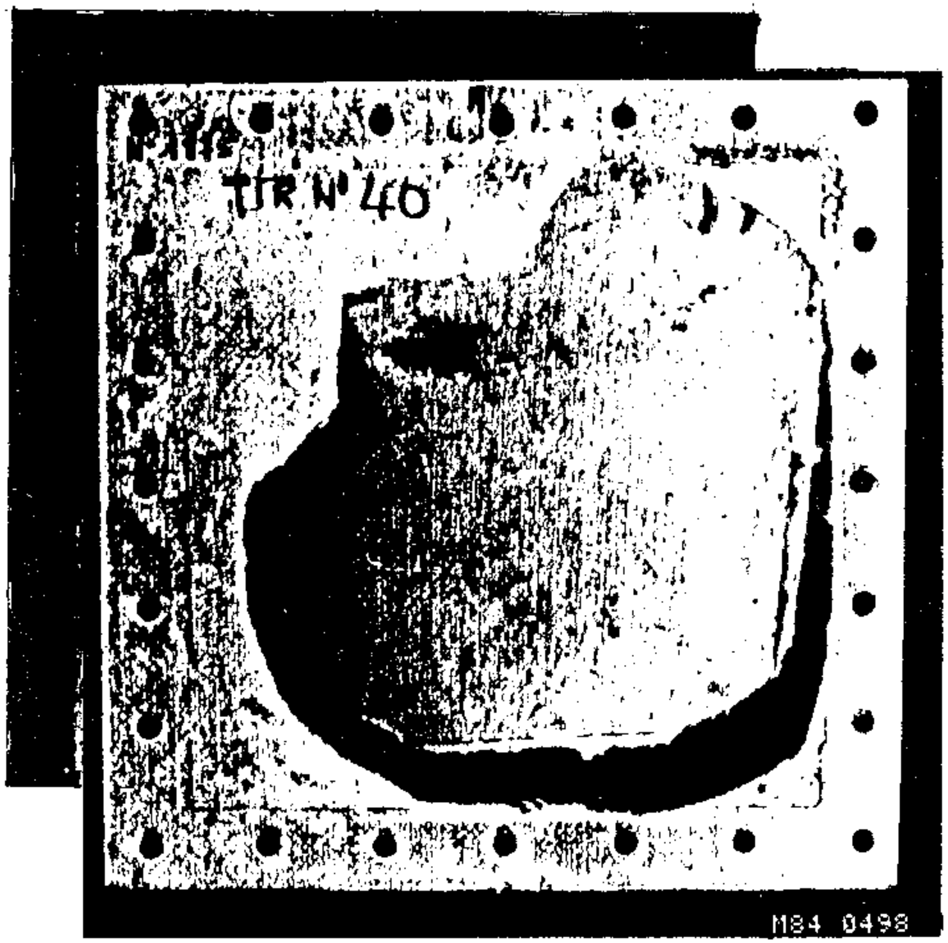
FIGURE 25

MONOLITHIC PLANE PLATES

NORMAL IMPACT

FAILURE PATTERN

STAR

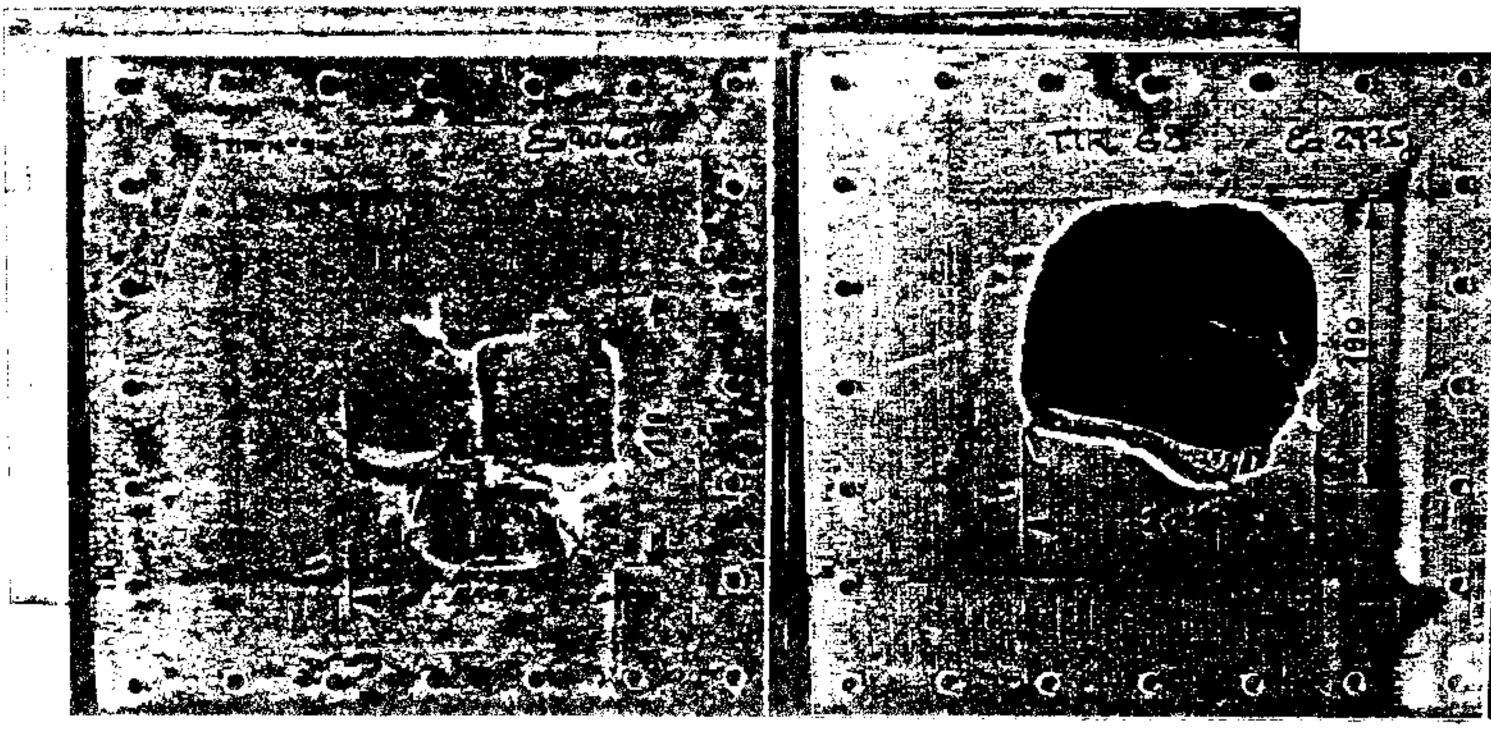


BOOK PAGE

FIGURE 26

PLANE PLATES SANDWICH

... HONEYCOMB CORE



PLANE PLATES SANDWICH

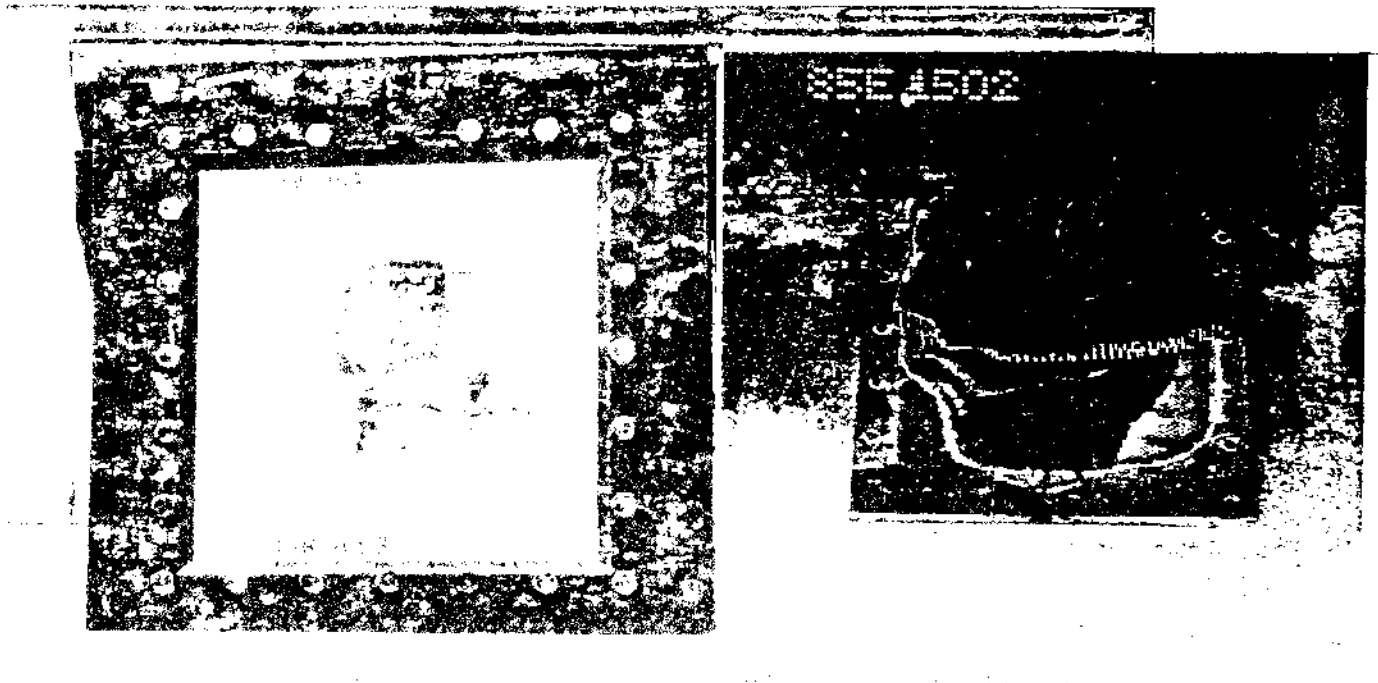
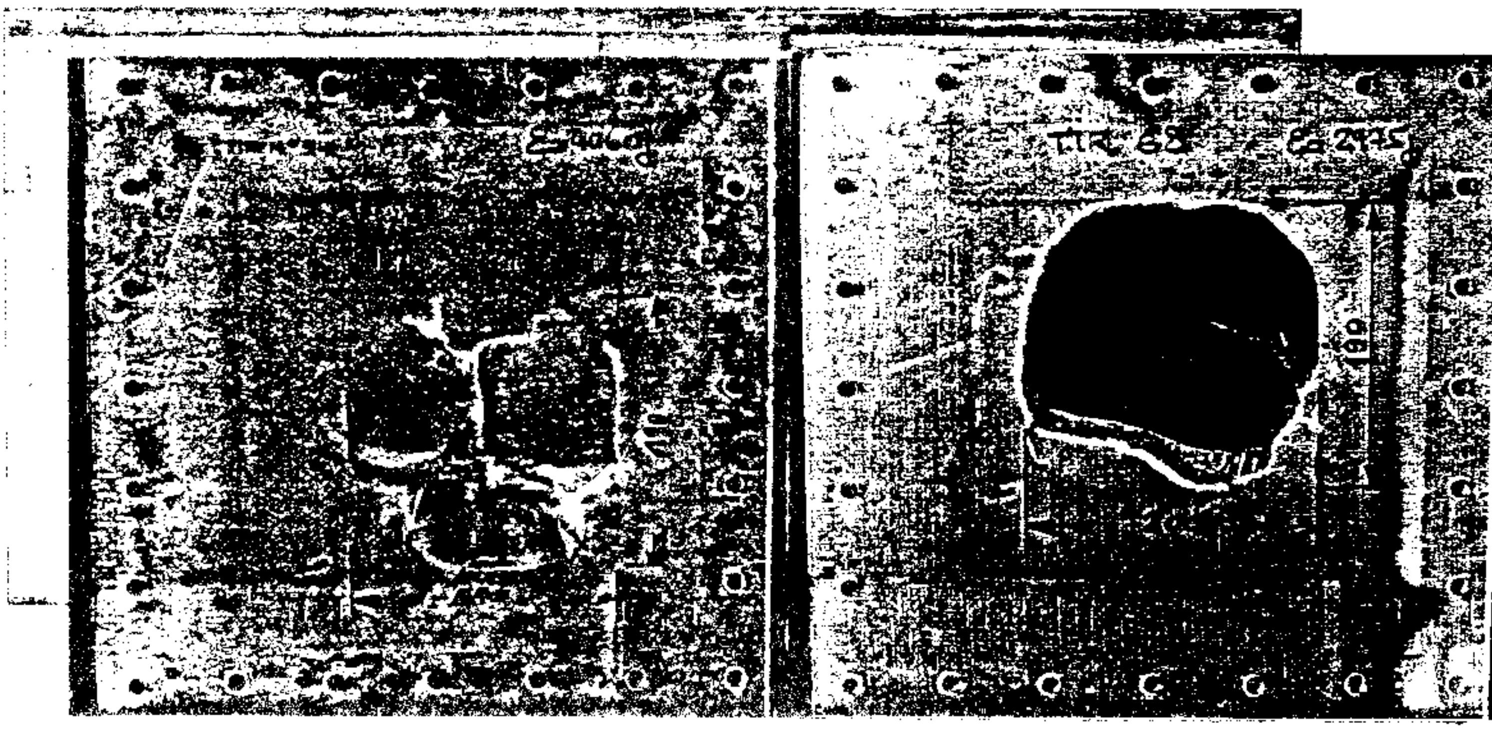


FIGURE 26

PLANE PLATES SANDWICH



PLANE PLATES SANDWICH

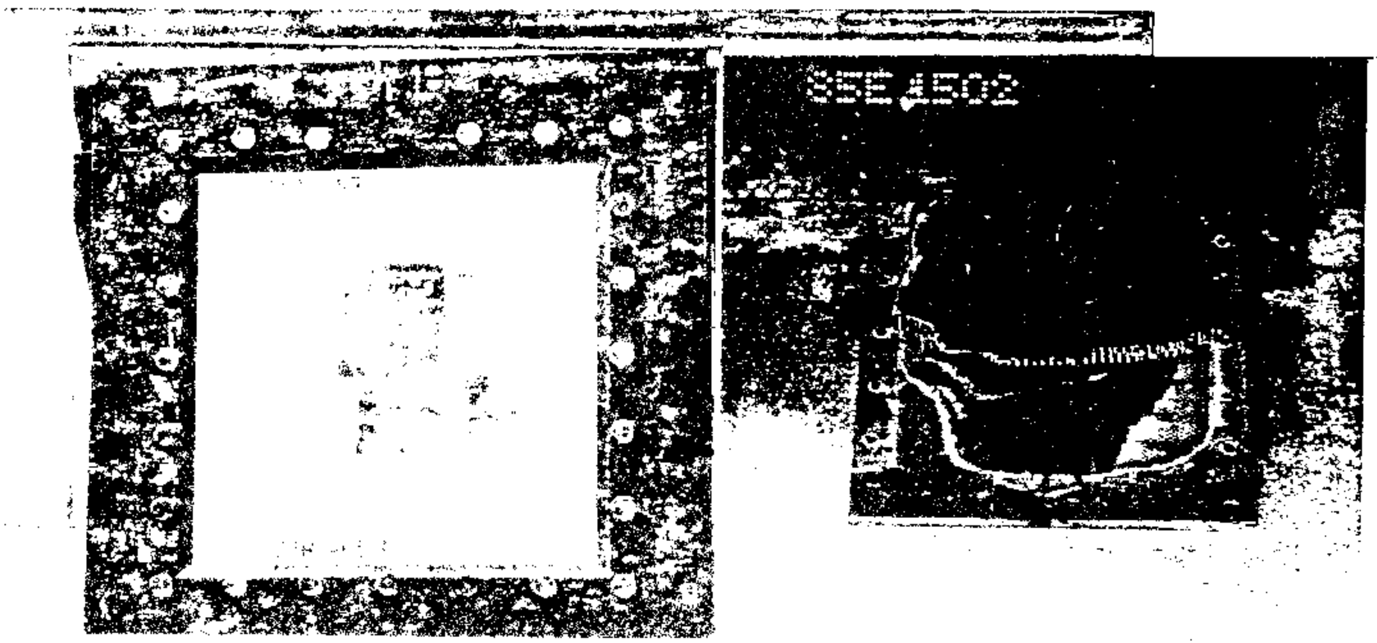


FIGURE 28

SANDWICH CURVED SPECIMENS

NORMAL IMPACT

FAILURE PATTERN

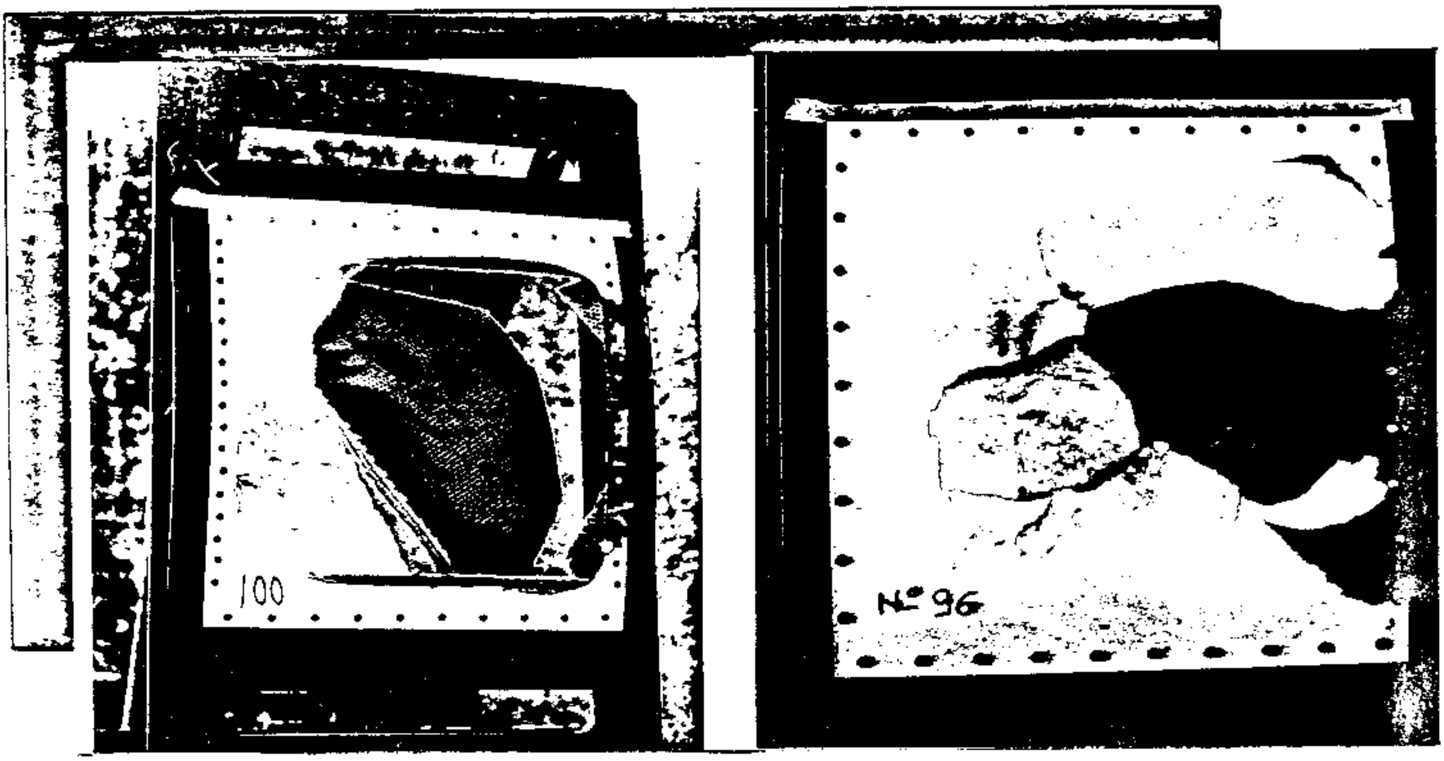


FIGURE 29

SANDWICH CURVED SPECIMENS

FAILURE PATTERN

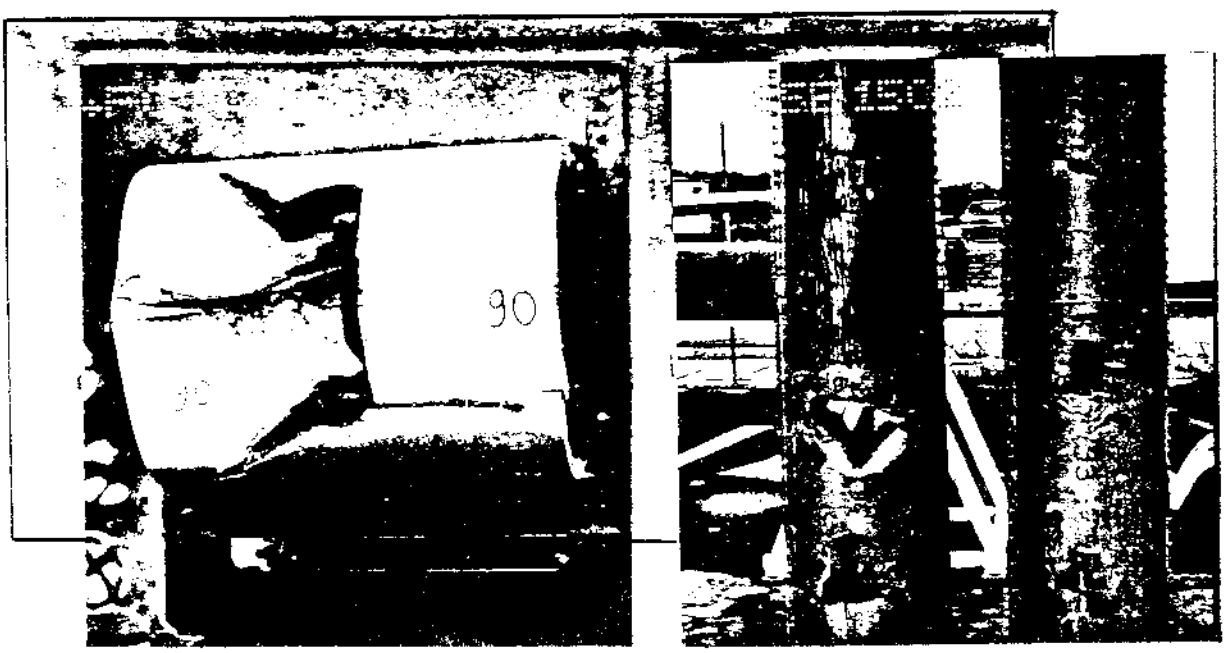


FIGURE 30

KEVLAR ® 49 MONOLITHIC PLANE PLATES

COMPARISON WITH 2024 T351

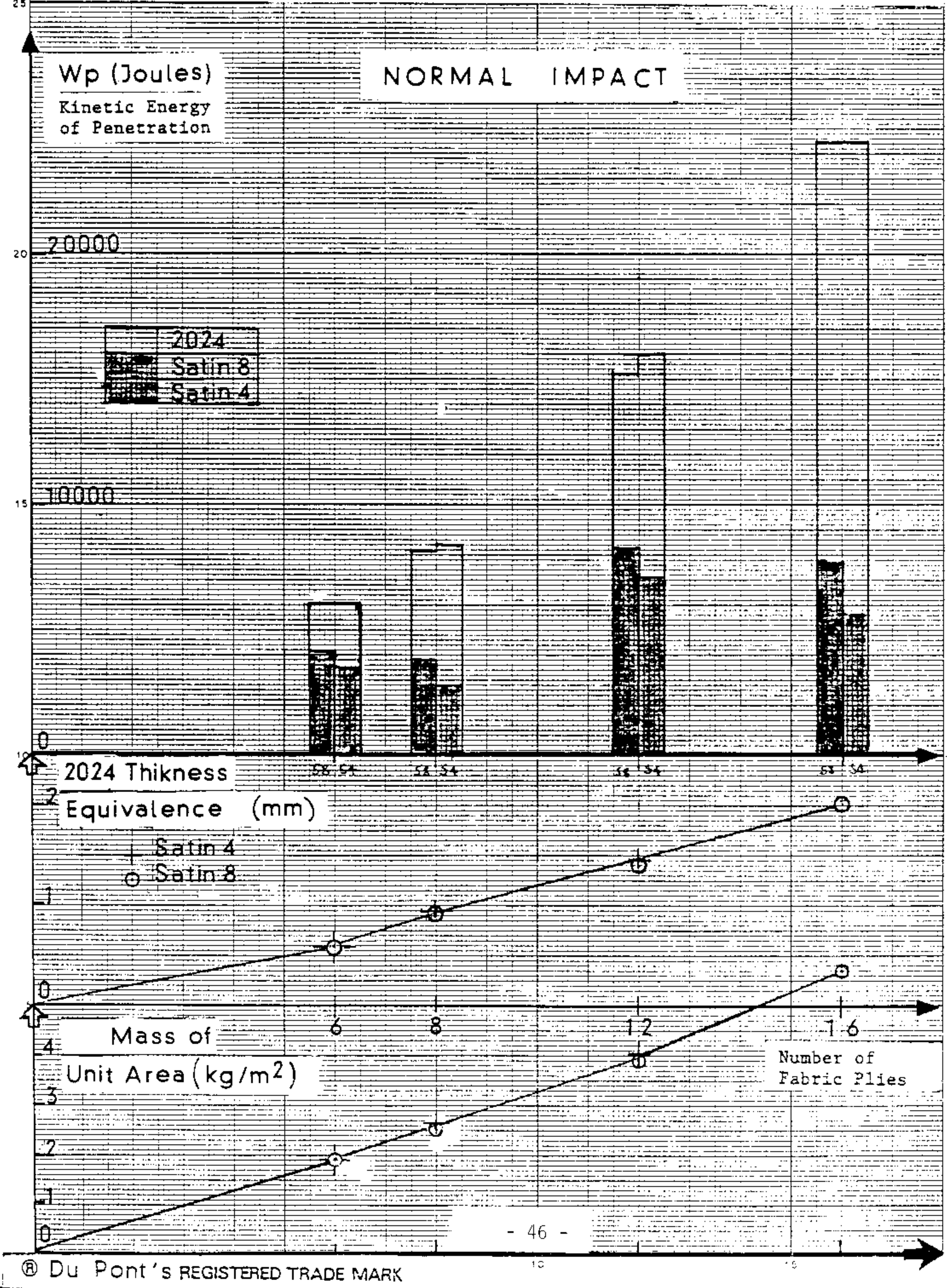


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FIGURE 31

KEVLAR ® 49 PLANE PLATES

Range of Kinetic Energy / Velocity Tested

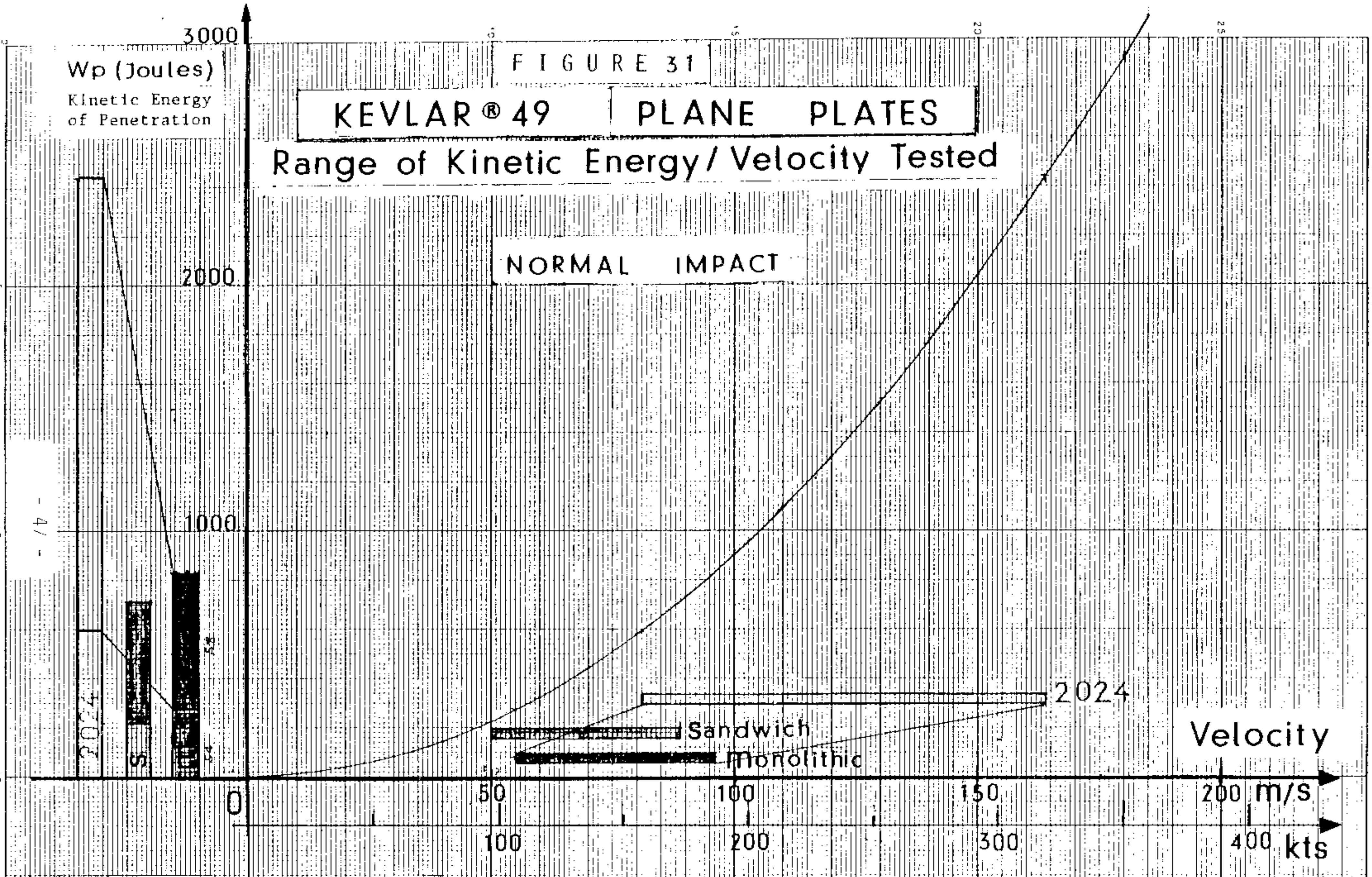

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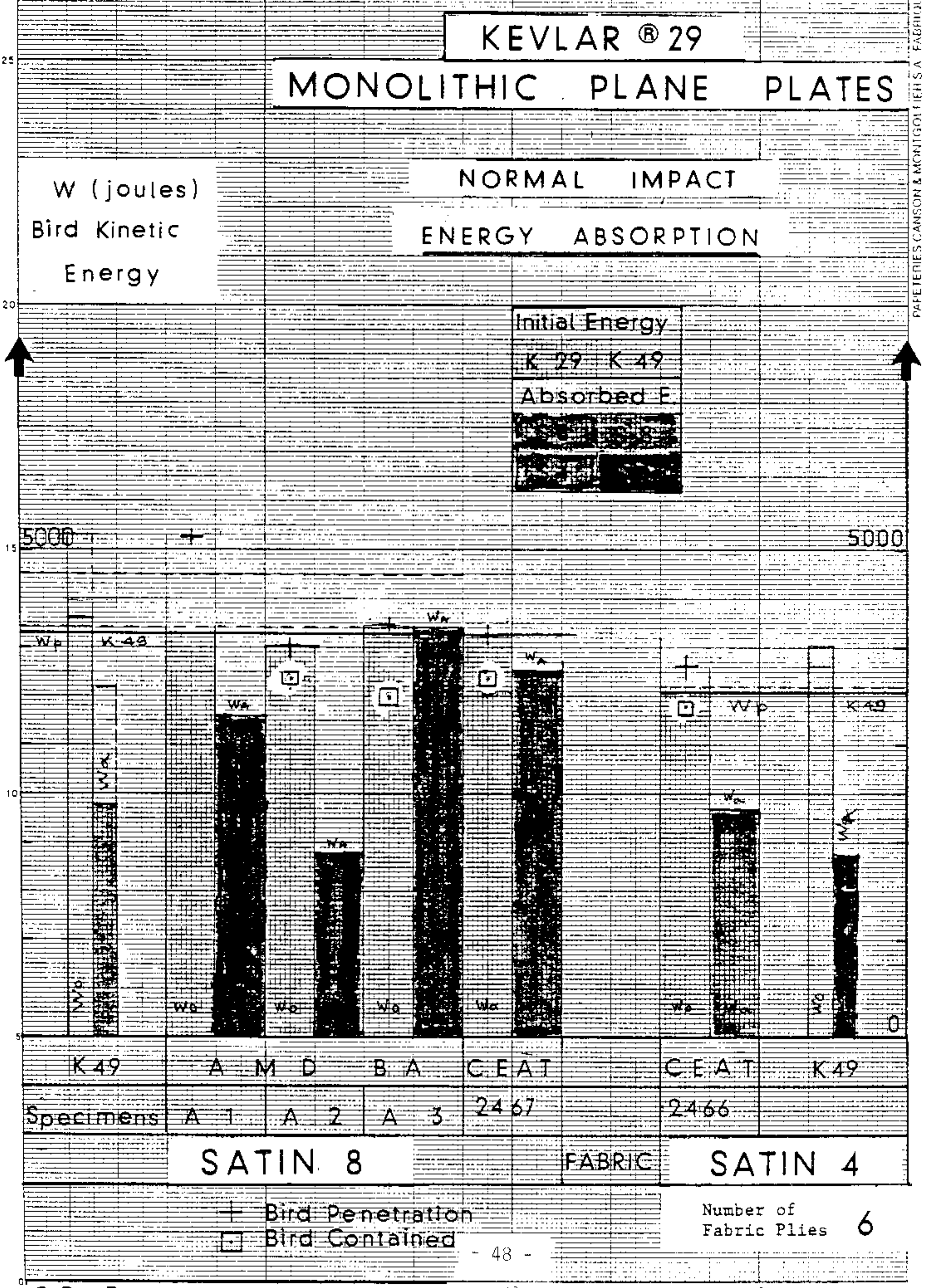
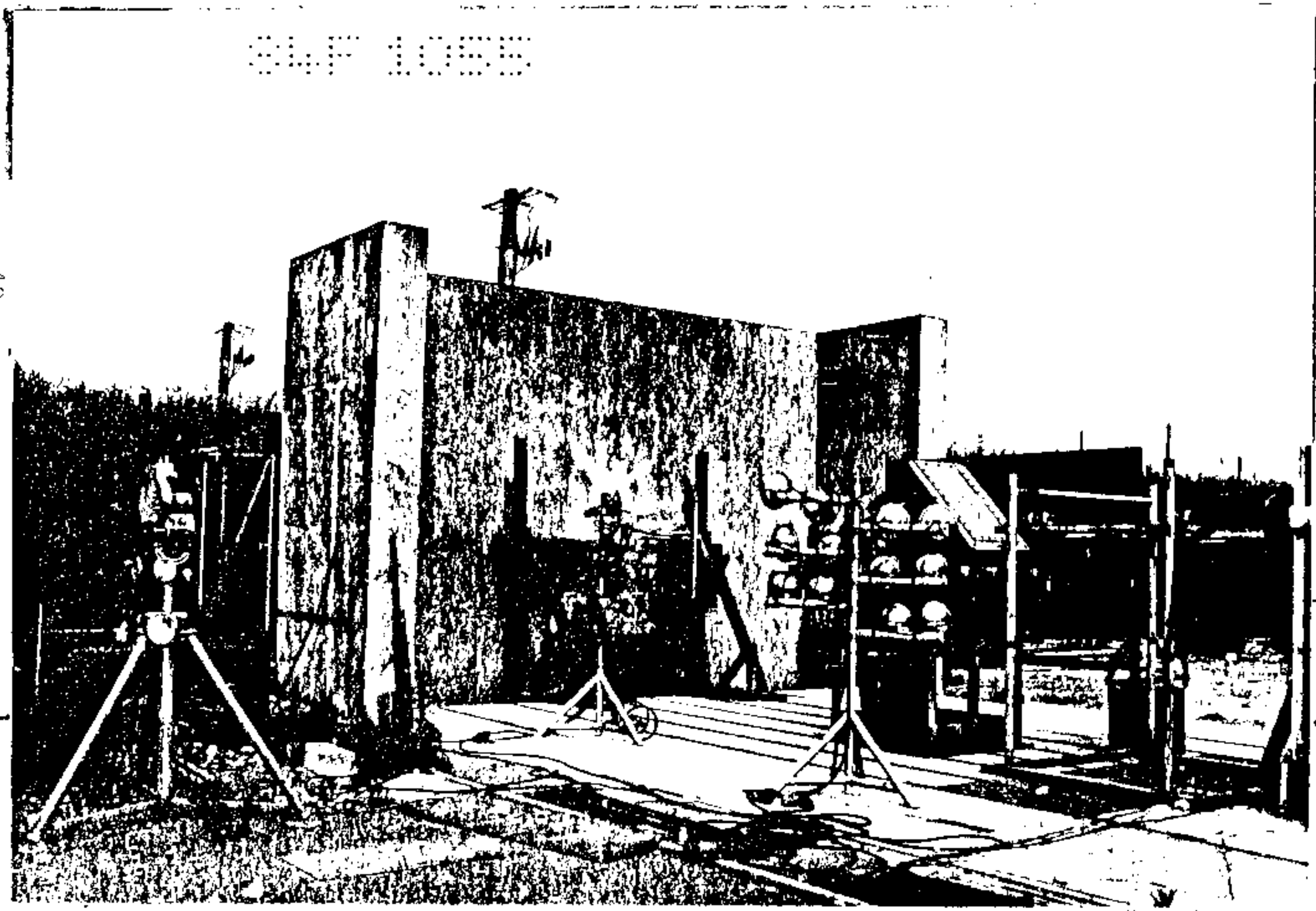
FIGURE 32

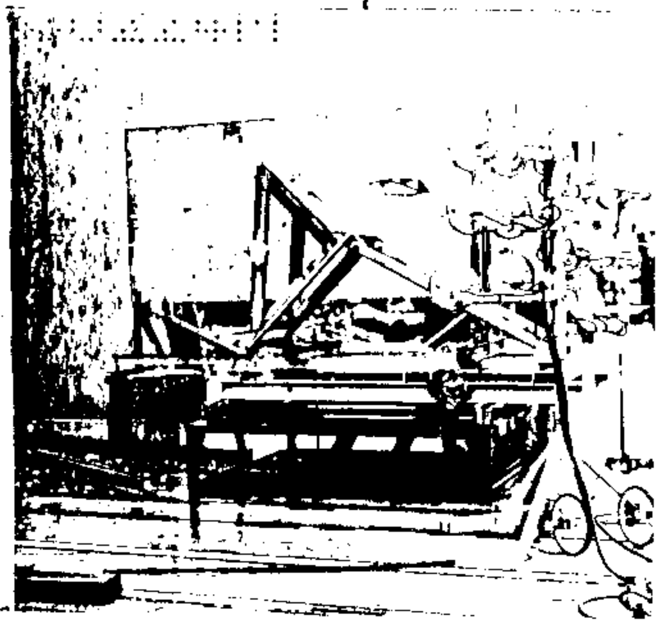


® Du Pont 's REGISTERED TRADE MARK

FIGURE 33

OBLIQUE IMPACT PRELIMINARY TESTS



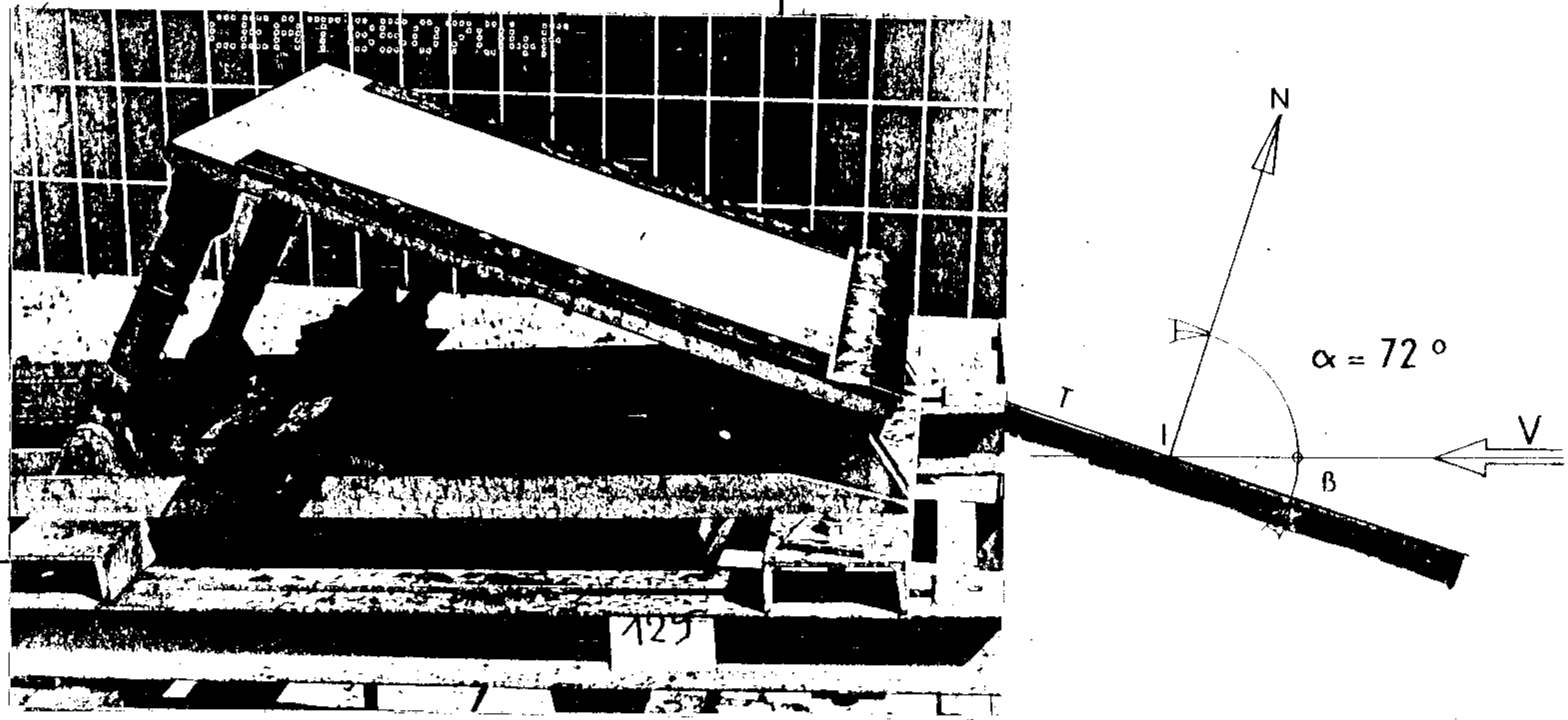


INITIAL TARGET SUPPORT

FIGURE 34

AMD-BA MONOLITHIC PLANE PLATES

PERIPHERAL ATTACHMENT



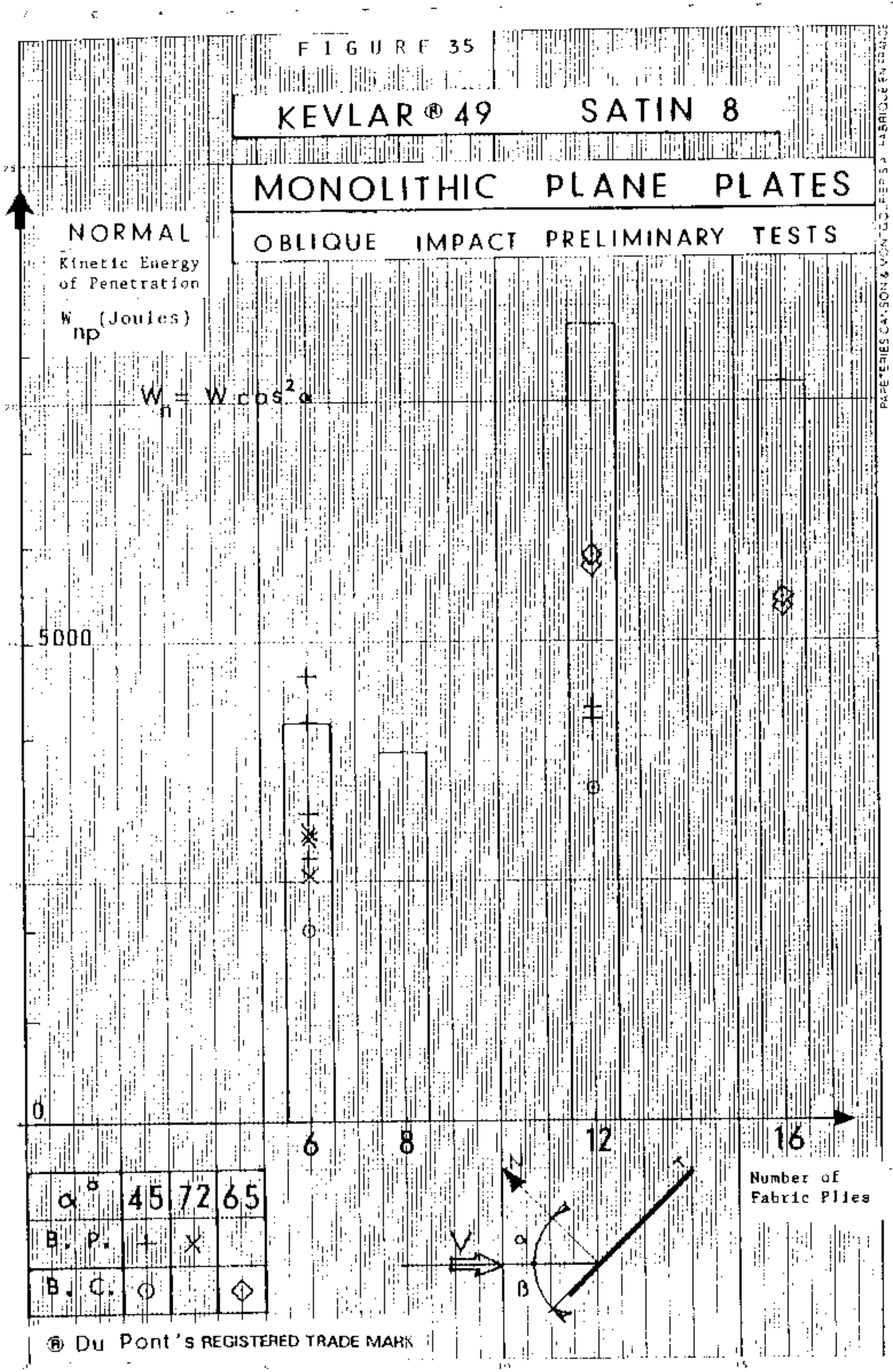


FIGURE 35
KEVLAR ® 49 SATIN 8
MONOLITHIC PLANE PLATES
OBLIQUE IMPACT PRELIMINARY TESTS
NORMAL
Kinetic Energy
of Penetration
W_{np} (Joules)
$W_n = W \cos^2 \alpha$
5000
0
6
8
12
16
Number of
Fabric Plies
α° 45 72 65
B. P.
B. C.
® Du Pont's REGISTERED TRADE MARK

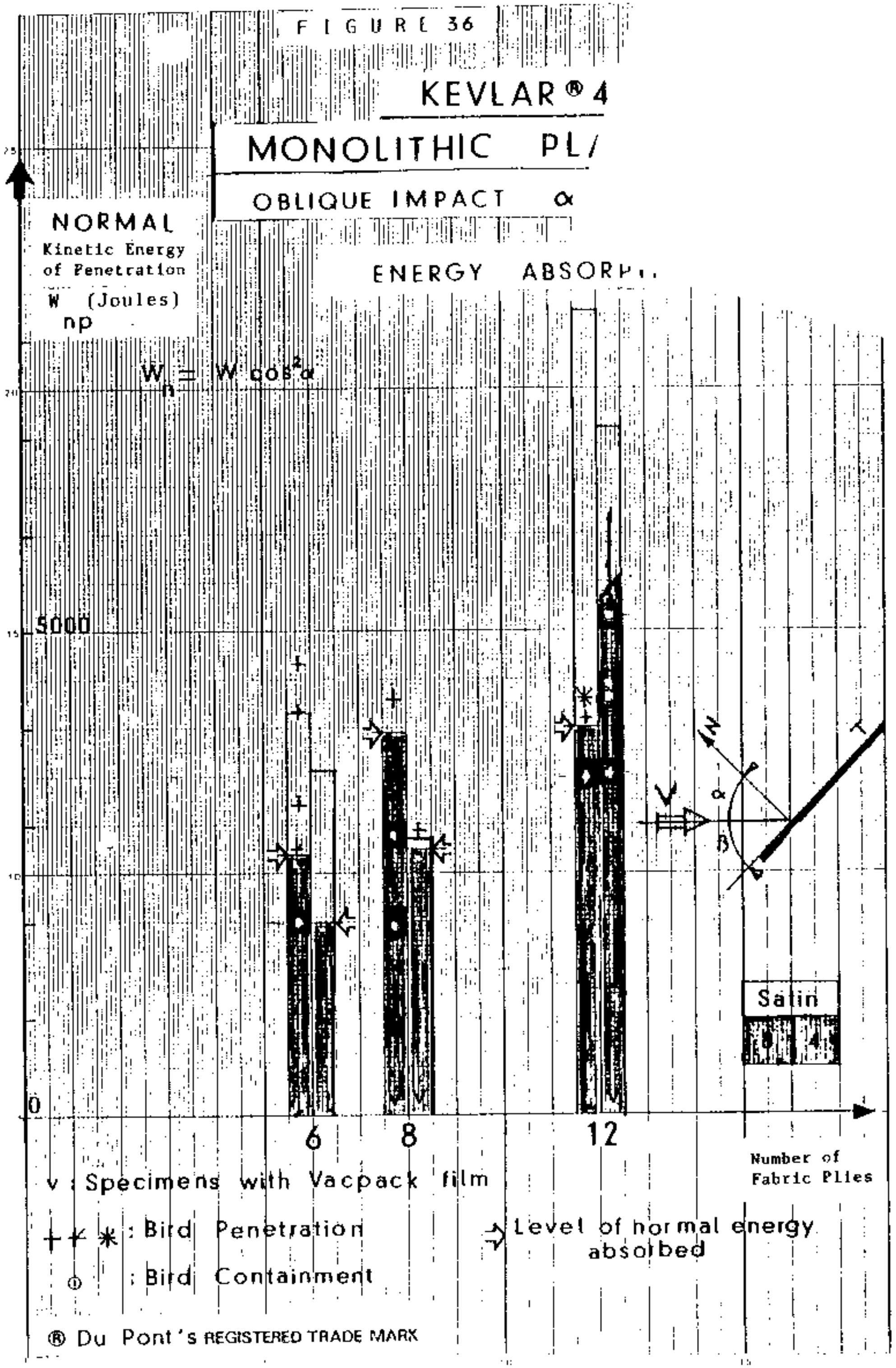


FIGURE 36
KEVLAR ® 4
MONOLITHIC PL/
OBLIQUE IMPACT α
ENERGY ABSORP
NORMAL
Kinetic Energy
of Penetration
W_{np} (Joules)
$W_n = W \cos^2 \alpha$
5000
0
6
8
12
Number of
Fabric Plies
Satin
v : Specimens with Vacpack film
: Bird Penetration
: Bird Containment
Level of normal energy absorbed
® Du Pont's REGISTERED TRADE MARK

FIGURE 37

AMD-BA SANDWICH CURVED SPECIMEN

Support For Oblique Impact

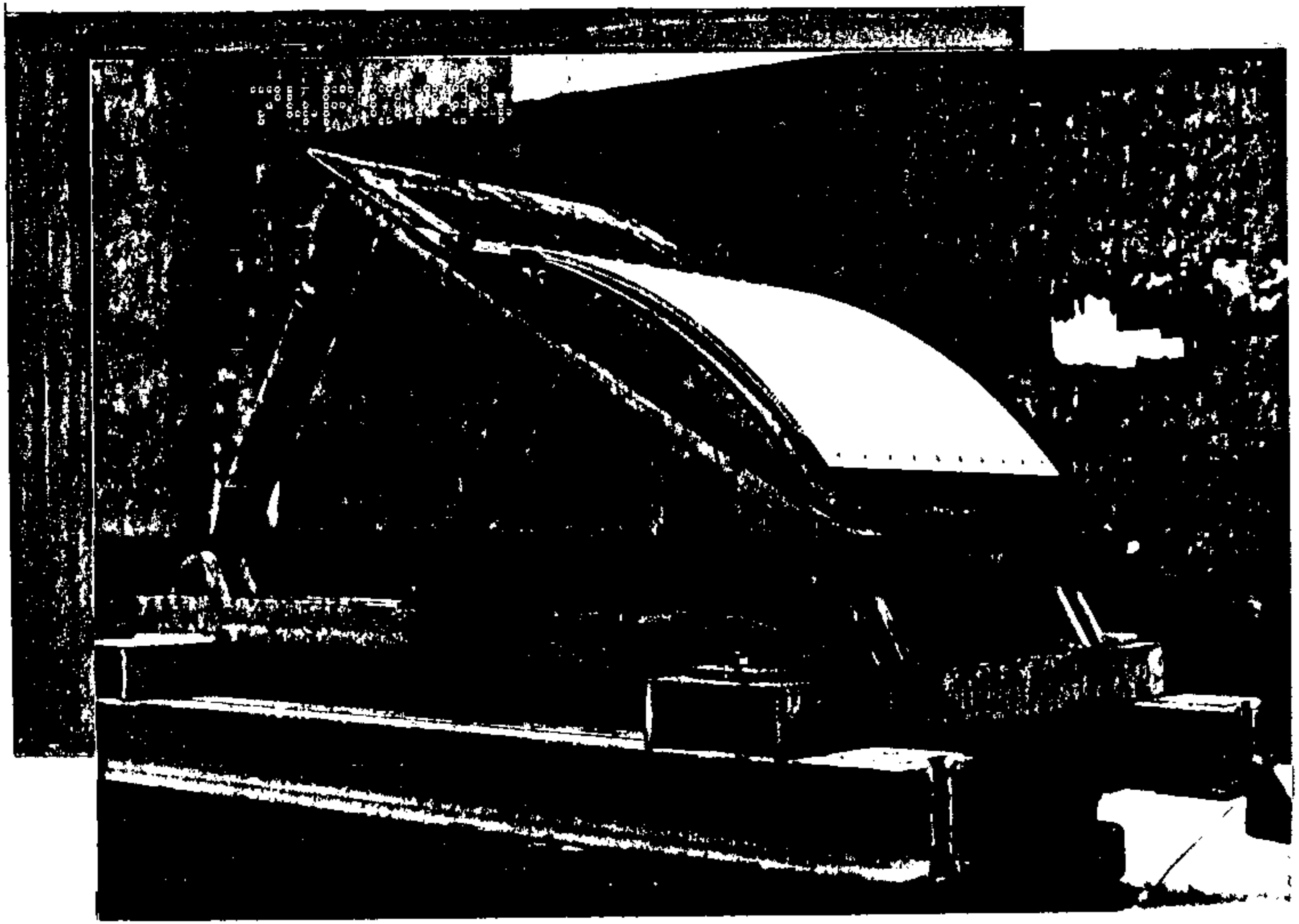


FIGURE 38

AMD-BA SANDWICH CURVED SPECIMEN

Oblique Impact $\alpha = 60°$

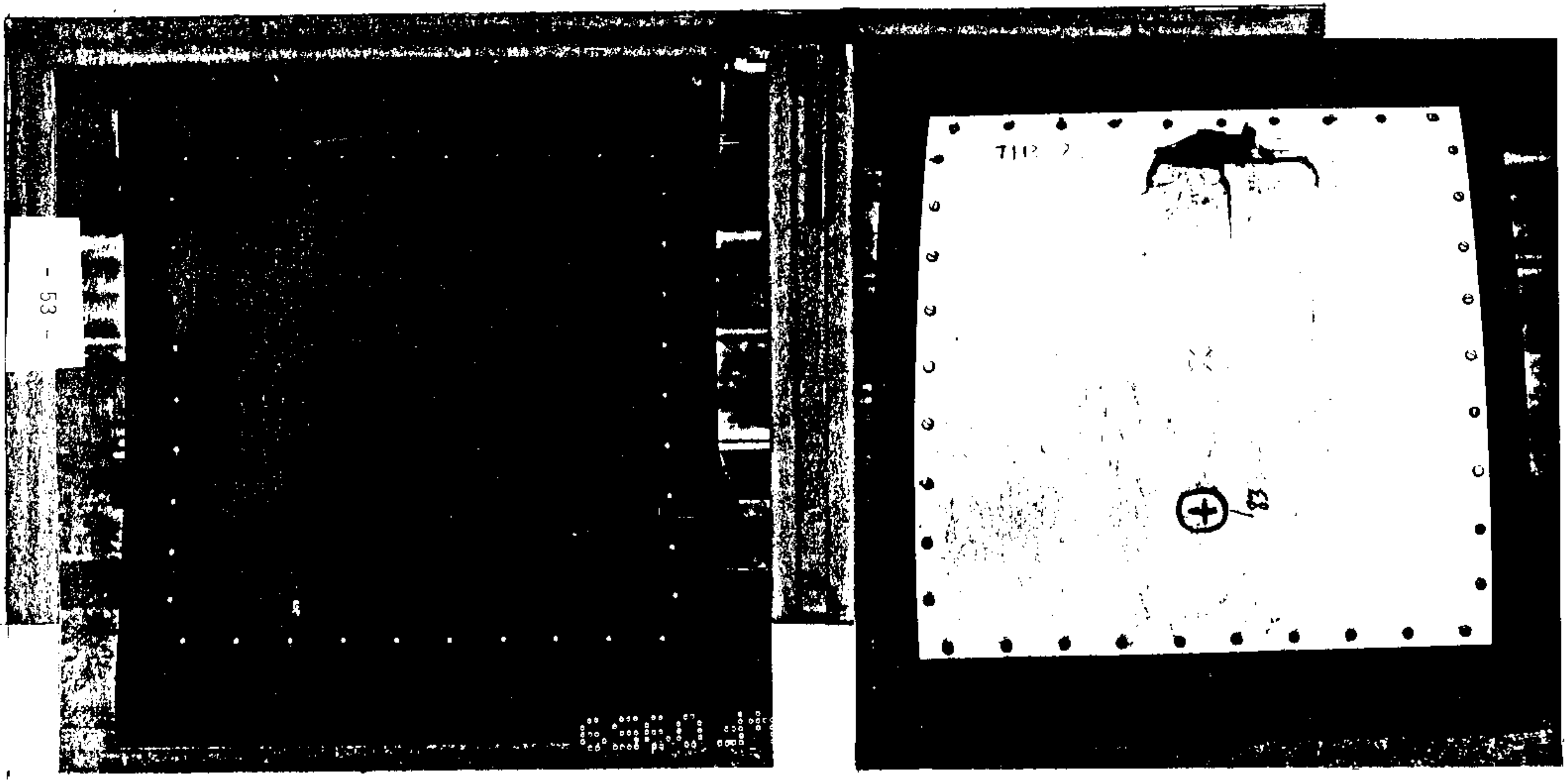
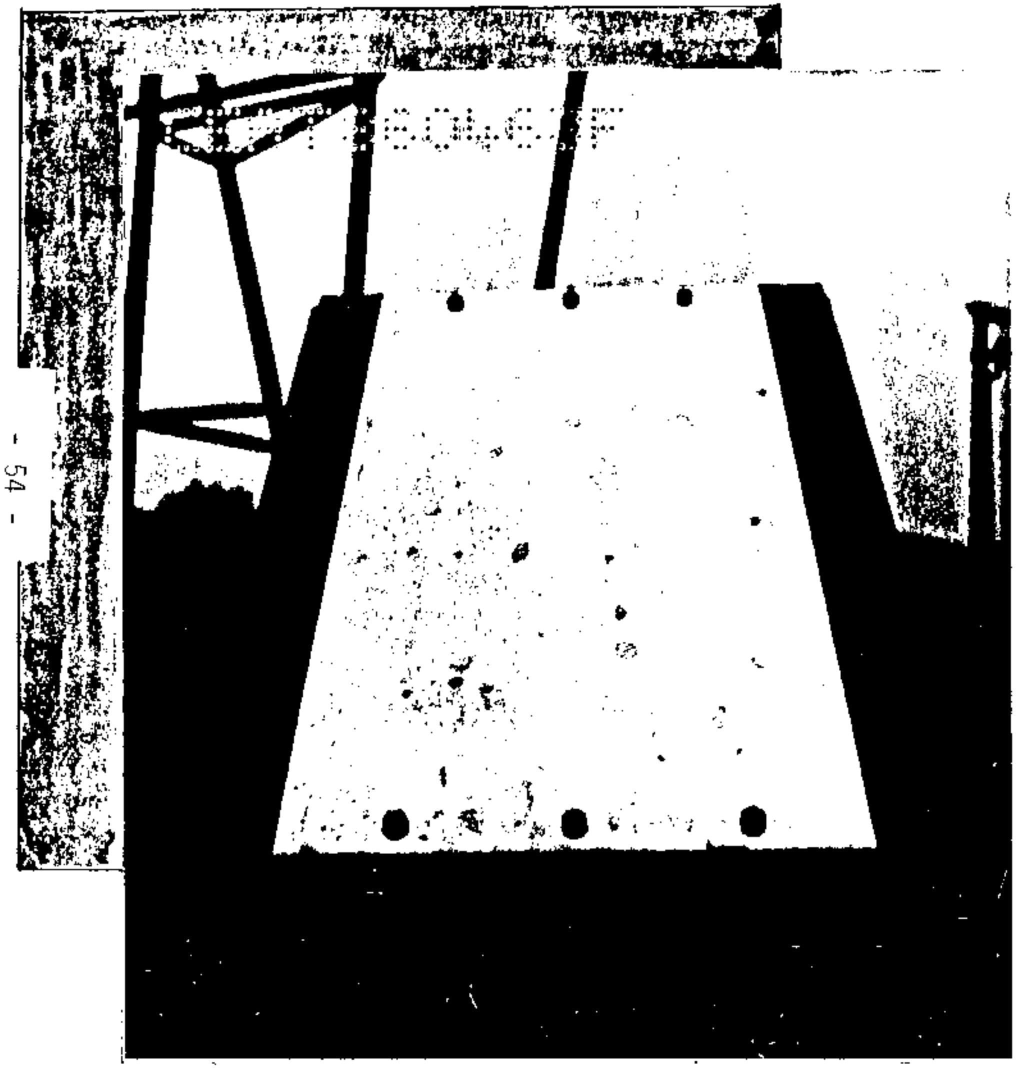


FIGURE 39

AMD-BA PLANE PLATES SANDWICH

WITH 2024 SKIN



Top and Bottom Attachment

INSTALLATION OF TEST SPECIMEN

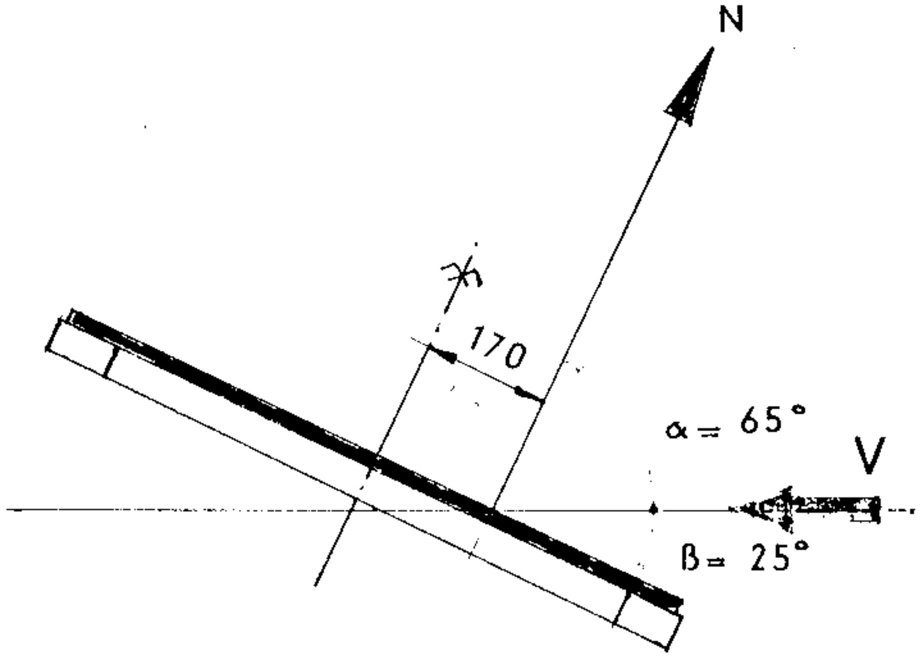
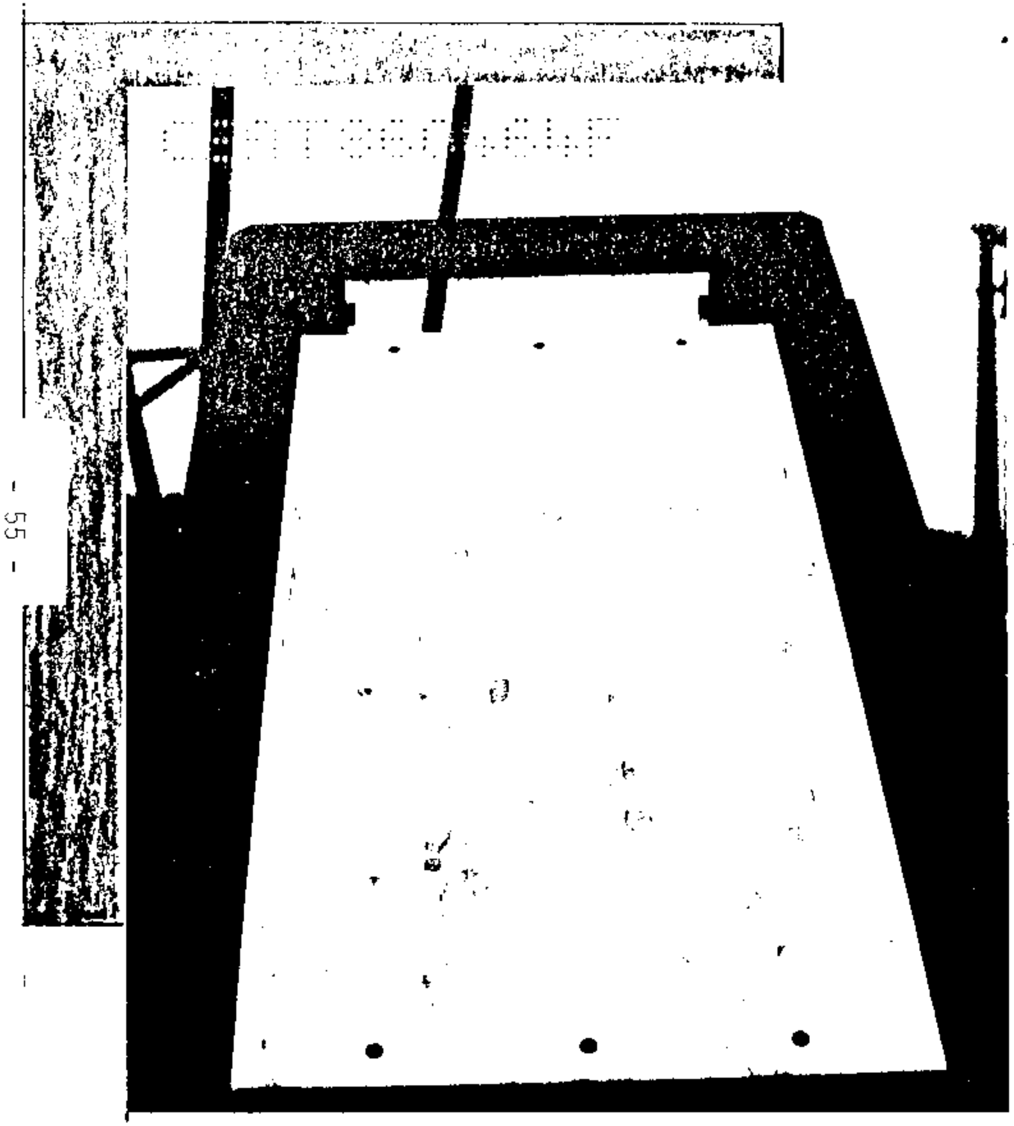


FIGURE 40

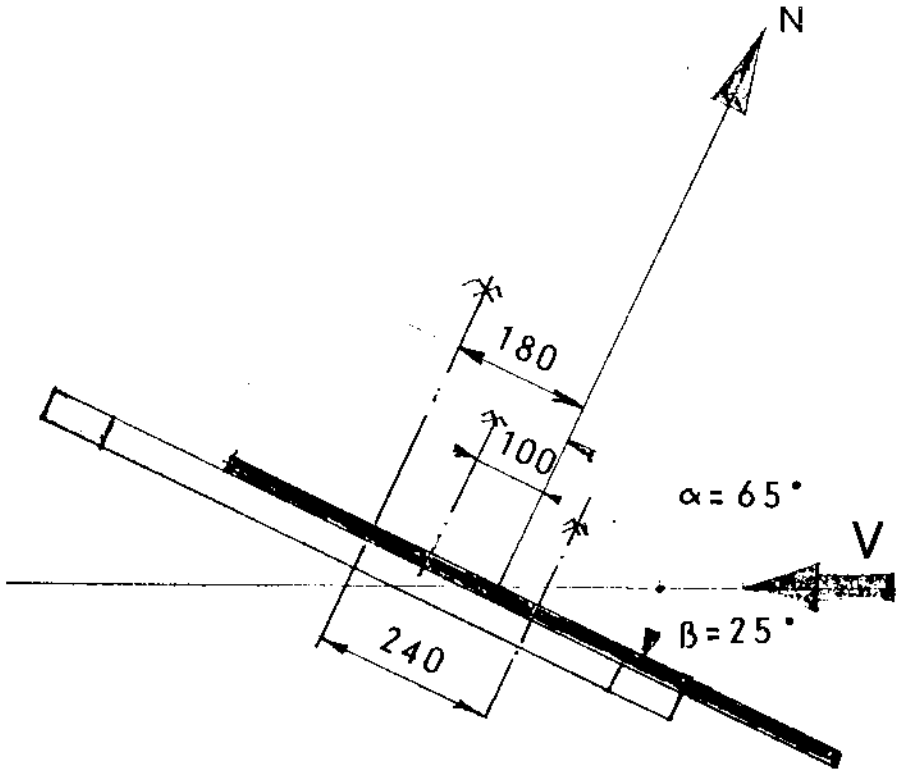
AMD-BA PLANE PLATES SANDWICH

WITH 2024 SKIN



Lateral Attachment

INSTALLATION OF TEST SPECIMEN



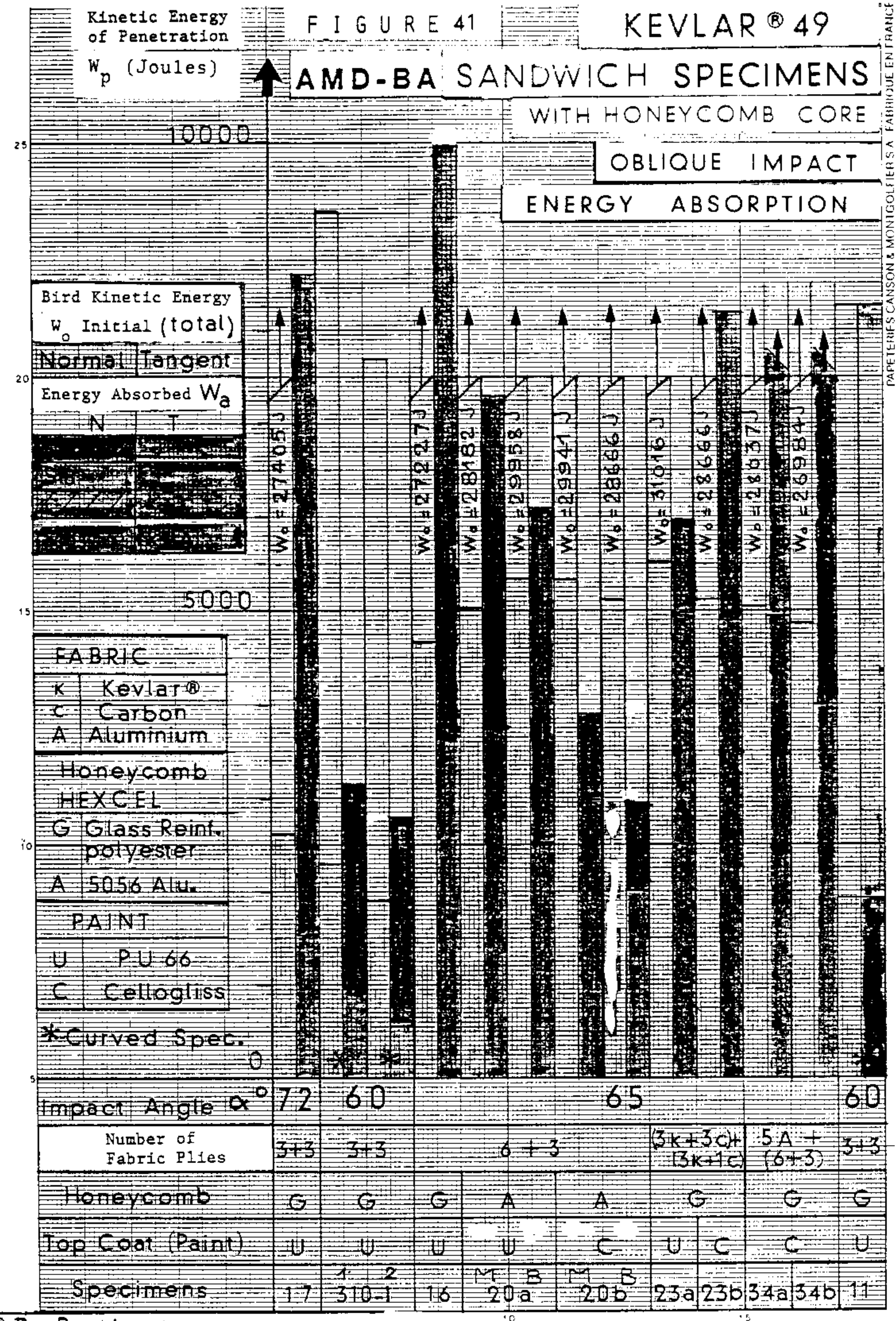


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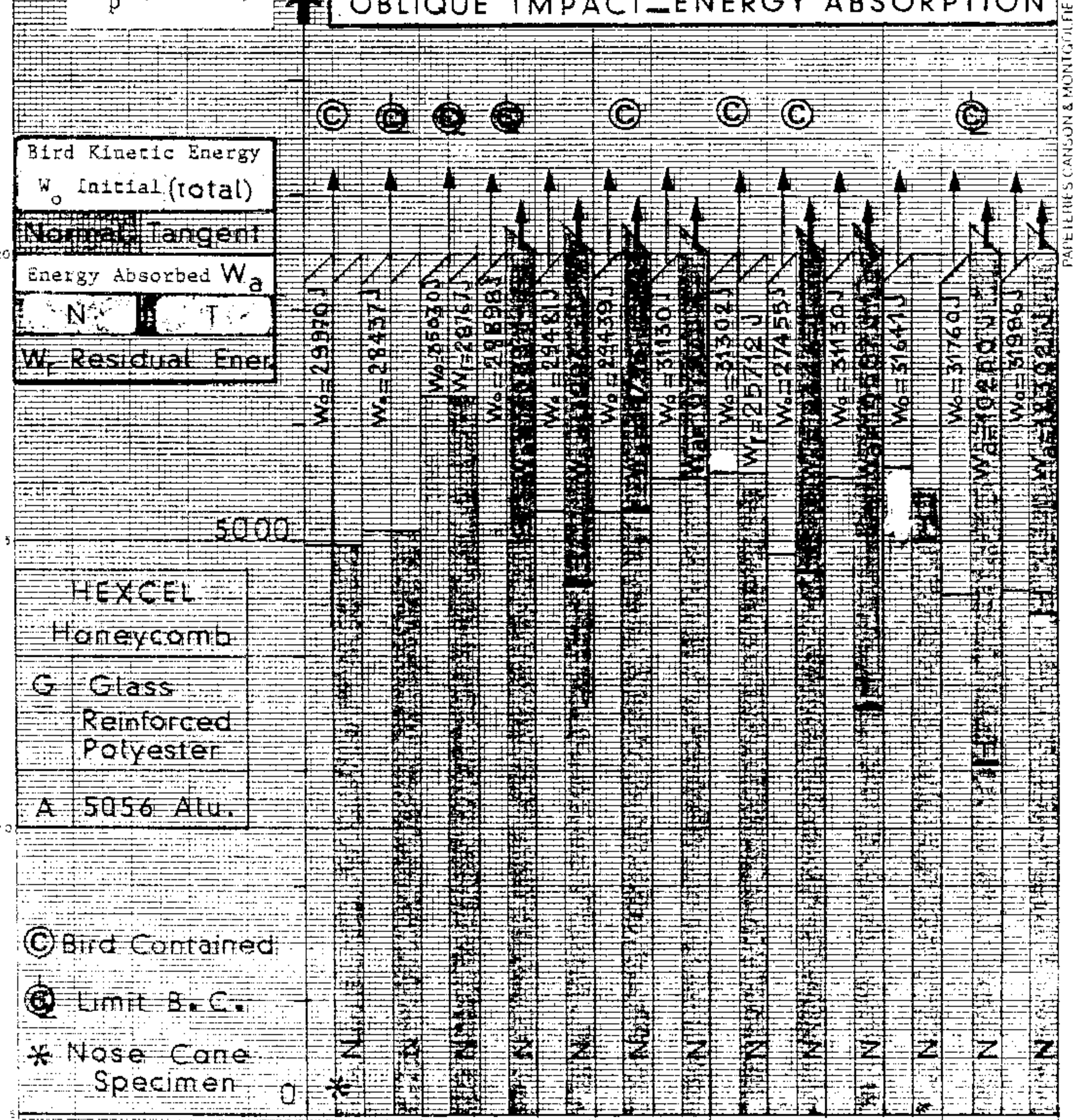
FIGURE 42 KEVLAR® 49 SATIN 8

AMD-BA SANDWICH SPECIMENS

WITH HONEYCOMB CORE & 2024 SKIN

OBLIQUE IMPACT—ENERGY ABSORPTION



Skin Thickness (mm)	0.6		0.4				0.6
Number of Fabric Plies			6+3				3+3
Honeycomb	G	G	A	A		G	G
Impact Angle α°	66	65	65	65		65	67.75
Specimens	*	21	22	32	29	30	33

® Du Pont's REGISTERED TRADE MARK

FIGURE 43

AMD-BA NOSE CONE TEST SPECIMEN

Installation of Test Specimen

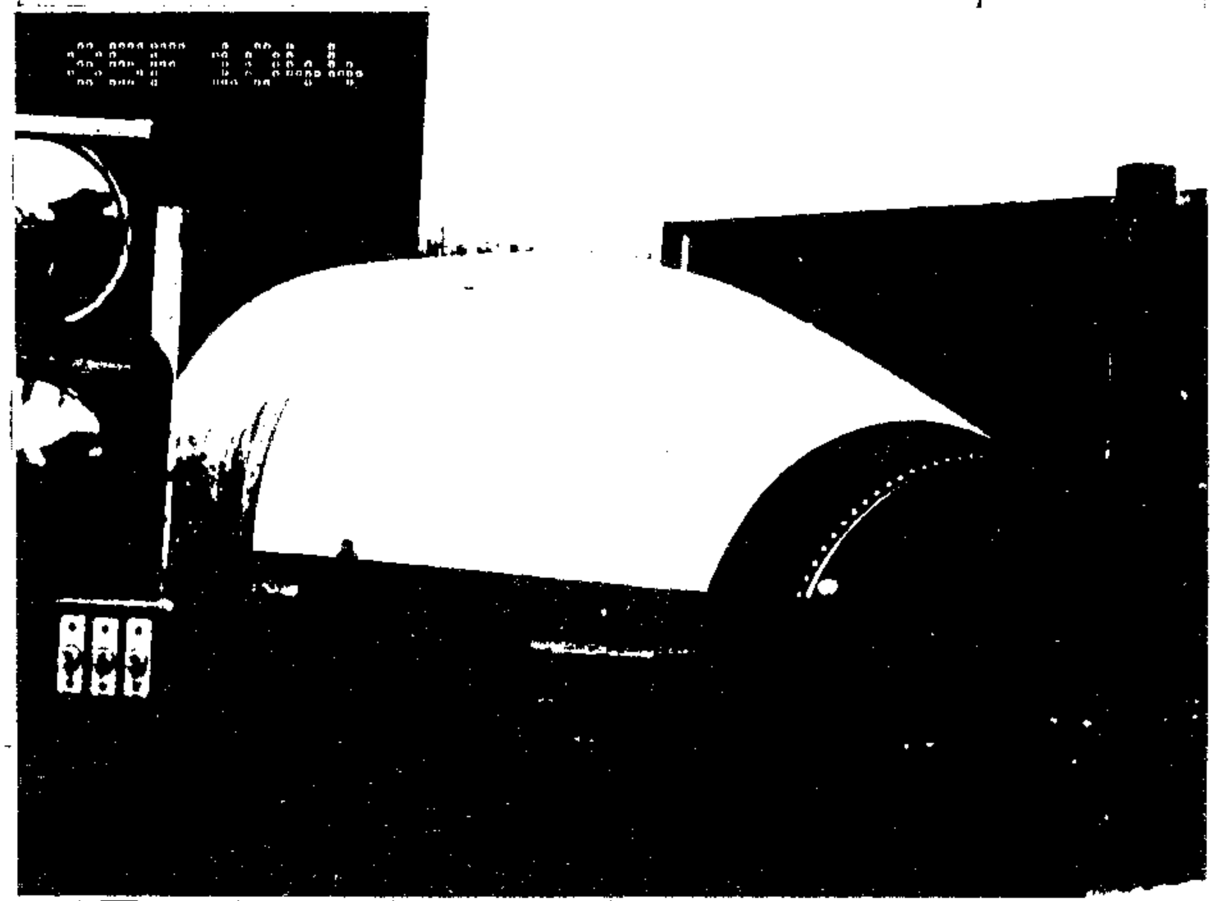


FIGURE 44

AMD-BA NOSE CONE TEST SPECIMEN

EXCERPTS FROM TEST PICTURE