46781
p. 33

NASA
Technical
Paper
3160

October 1991

An Examination of the Damage Tolerance Enhancement of Carbon/Epoxy Using an Outer Lamina of Spectra®

D. G. Lance
and A. T. Nettles

NASA

NASA
Technical
Paper
3160

1991

An Examination of the Damage Tolerance Enhancement of Carbon/Epoxy Using an Outer Lamina of Spectra®

D. G. Lance
and A. T. Nettles
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

LIST OF ILLUSTRATIONS

TECHNICAL PAPER

AN EXAMINATION OF THE DAMAGE TOLERANCE ENHANCEMENT OF CARBON/EPOXY USING AN OUTER LAMINA OF SPECTRA®

MSFC Center Director's Discretionary Fund Final Report, Project No. 90-17

I. INTRODUCTION

Low-velocity, foreign-object impact damage of carbon fiber-reinforced composite materials is an area of great concern because of the low damage tolerance level associated with these materials. It is widely understood that the impact resistance of the carbon fiber/epoxy resin systems must be improved before these materials will become utilized to a great extent in high performance structures. Efforts to improve the ability of composites to withstand damage have included the manufacturing of new system components. Carbon fibers with a much higher strain to failure and a higher strength have been created as well as new damage tolerant resins.[1] Another means of enhancing the impact resistance of the carbon/epoxy composite is through utilizing a hybrid system.[2–5,14] By combining a high-tensile-strength, high-strain fiber with the carbon/epoxy system, a significant increase in damage tolerance may possibly be achieved with a minimal increase in weight. A layer of ultra-high molecular-weight polyethylene (UHMWPE) fibers on the outside surface of the composite panel has the potential to act as an impact energy dissipator, allowing the material to suffer less damage for a given impact force.

Low-velocity instrumented impact testing is an established experimental method for investigating the damage tolerance of composite and hybrid materials.[1–3,6,7] Data from impact tests such as maximum load at impact, force-time plots, absorbed energy from impact, and deflection are important in order to characterize the materials. Compression after impact testing is a standard method of measuring residual strength and thus the extent of the damage to the composite material.[3,8–11] Comparisons can be made between the residual strength of a specimen and the data from its instrumented impact. Another destructive test method, cross-sectional cutting through the impact site, is also an established process for revealing damage sustained during impact.[1,7,12,13] Documentation by photography of the specimen both internally and externally provides an opportunity for comparison of the damage tolerance between materials and lay-up configurations. In addition, comparisons can be made between the visual damage, the instrumented impact data, and residual strength data.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Materials

The specimens investigated in this study were panels of a hybrid system of carbon fiber/epoxy resin and UHMWPE. The graphite prepreg was designated T300/948. The T300 fibers were produced by AMOCO and impregnated by Fiberite with their 948 resin. The UHMWPE fibers were manufactured in prepreg form with a thermoplastic resin by Allied-Signal under the trade name Spectra Shield. The film adhesive used to bond the Spectra to the carbon/epoxy panels was a thermoset epoxy obtained by Hysol and designated EA 9684.

The T300/948 was chosen for this study for its low temperature cure of 121 °C (250 °F), which was necessary because the melting point of UHMWPE is 127 °C (260 °F), and because of its similarity to T300/934 of which a wide data base exists. The T300 is an intermediate modulus fiber, and the 948 is a standard (untoughened) epoxy resin.

The T300/948 prepreg was layered into 16-ply quasi-isotropic panels $(0,-45,90,+45)_{S2}$. Specimen panels were constructed without UHMWPE, with UHMWPE on one side, and with UHMWPE on both sides. Panels were also fabricated using the EA 9684 film epoxy to bind the UHMWPE to the bottom side of the T300/948. Each configuration was cured in a programmable platen press at a temperature of 127 °C (260 °F) and at the pressure and for the duration recommended by the manufacturer. The cure temperature used was 5.6 °C (10 °F) higher than the normal processing temperature so that the UHMWPE would better adhere to the carbon composite.

The T300/948 specimens had an average thickness of 2.14 mm. The T300/948 with a layer of UHMWPE on one side had an average thickness of 2.34 mm. The T300/948 with a layer of UHMWPE on each side had an average thickness of 2.49 mm. The T300/948 with a layer of EA 9684 bonding the UHMWPE had an average thickness of 2.43 mm.

Square plates measuring 10.2 cm (4.0 in) on a side were machined from the composite panels for the specimens that would be cross-sectionally cut after impact testing. Specimens measuring 17.9 by 7.7 cm (7.0 by 3.0 in) were machined from the composite panels for the compression-after-impact testing. Fiberglass end tabs that were 3.8 cm (1.5 in) wide were bonded on both sides of each specimen.

B. Impact Testing

The specimens were impacted using a Dynatup model 8200 drop weight apparatus. The data were obtained with a Dynatup 730 data acquisition system and an IBM computer. The impactor had a mass of 1.77 kg and a hemispherical tup with a diameter of 1.27 cm (0.5 in). The specimens to be cross-sectioned were held fast by two aluminum plates that were pneumatically clamped. The plates had 7.62-cm (3.0-in) diameter holes through which the composite was exposed. Because of the clamp interference by the fiberglass tabs, the compression-after-impact specimens were held fast using a specially designed pneumatic clamping system. The aluminum plates that held these specimens measured 10.2 by 7.6 cm with 6.4-cm (2.5-in) holes in the center. Three specimens of each UHMWPE configuration were damaged at each of the seven impact energy levels used for the purpose of cross-sectioning. Six specimens of each configuration were damaged at an impact energy level of approximately 6.1 J for compression tests.

C. Visual Damage

The damage to both surfaces of the specimens of each configuration at each energy level was recorded and photographed using a 35 mm camera.

D. Specimen Cross Sectioning

One specimen of each hybrid configuration from each of the seven impact energy levels was cross-sectionally cut, perpendicular to the outer fibers, through the impact site. The cut was made with a Buehler diamond wafering blade. The specimens were examined and photographed using a Zeiss stereo-optical microscope with a Zeiss MC100 automatic camera attachment. The specimens were magnified by × 16 when photographed.

E. Compression Testing

Compression-after-impact testing was conducted on an Instron 1125 testing machine. The tests were performed at a strain rate of 1.3 mm/min. Six specimens of each configuration were tested. Three specimens without UHMWPE that were not impacted were compression tested for comparison purposes. A drawing of the modified Celanese/IITRI compression test fixture used during this project is presented in figure 1. A patent has been applied for this device and detailed documentation is available.[5]

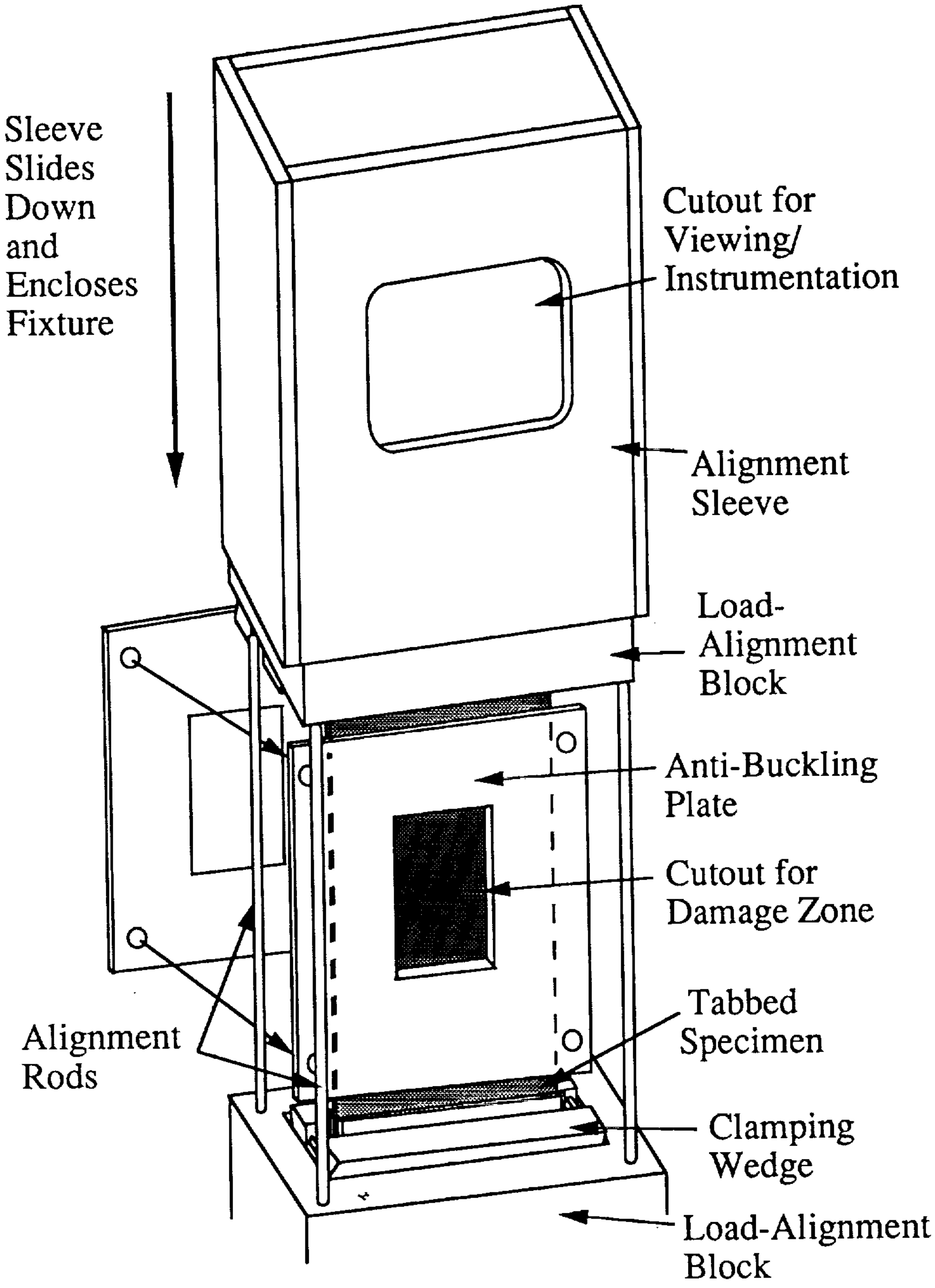


Figure 1. Modified fixture to test residual compression strength.

III. RESULTS AND DISCUSSION

A. Plots From Impact Tests

Force-time and absorbed energy-time plots were generated by the data acquisition system for each specimen tested. At drop height levels that result in fiber breakage, a large drop in force can be noticed on the plots. The absorbed energy-time graphs are smooth curves superimposed on the force-time plots. Specimen damage explains only part of the energy loss recorded as absorbed energy. The plots for several impacts are provided in the appendix.

B. Maximum Load Versus Impact Energy Graphs

Graphs were made which plotted the maximum load of each impact event against the respective impact energy. The plots of each configuration are somewhat linear until the point that fiber breakage occurs. The correlation between the maximum force and increasing impact energy becomes more horizontal and the points become more scattered after fiber breakage initiates. Graphs of each UHMWPE configuration are given in figures 2 through 6. For comparison purposes, all the graphs are superimposed together in figures 7 and 8. Figure 7 shows that the plot of all the materials follows that of an inverse parabolic curve. It also shows that there is no distinctively different curve for each of the configurations used.

C. Visible Surface Damage

The visible surface damage after impact was recorded and photographed for each specimen. Photographs of selected specimens are displayed in the appendix. A description of the surface damage to each UHMWPE configuration is given below.

The T300/948 plates without UHMWPE first displayed damage at 4.1 J when a crack appeared on the back (nonimpacted surface). At the 6.0-J energy level, a visible dent occurred at the impact sight. Fiber breakage was noticed on the back surface at the 7.1-J impact energy level.

The T300/948 with a layer of UHMWPE on the top surface first sustained visible damage with a crack that appeared on the back surface at 4.1 J. A dent was noticed at the point of impact with the 6.1-J energy level.

The T300/948 with a layer of UHMWPE on the bottom surface prevented visible damage until 4.0 J when a slight mark was made on the back surface due to the crazing of the Spectra fiber. At the next impact level of 6.0 J, the back surface was significantly cracked beneath the layer of UHMWPE which accounted for the raised area of crazing. A dent occurred on the front at 7.2 J.

The T300/948 with a layer of UHMWPE on both surfaces displayed damage for the first time with a crazing mark on the back surface at 5.1 J. The back surface was raised underneath the crazing at 6.1 J. A dent was visible at the site of impact for the 7.2-J energy level.

The T300/948 with a layer of film epoxy and UHMWPE on the bottom surface displayed crazing at 2.3 J. The raised back was apparent at 5.1 J. The front dent was visible at 7.1 J.

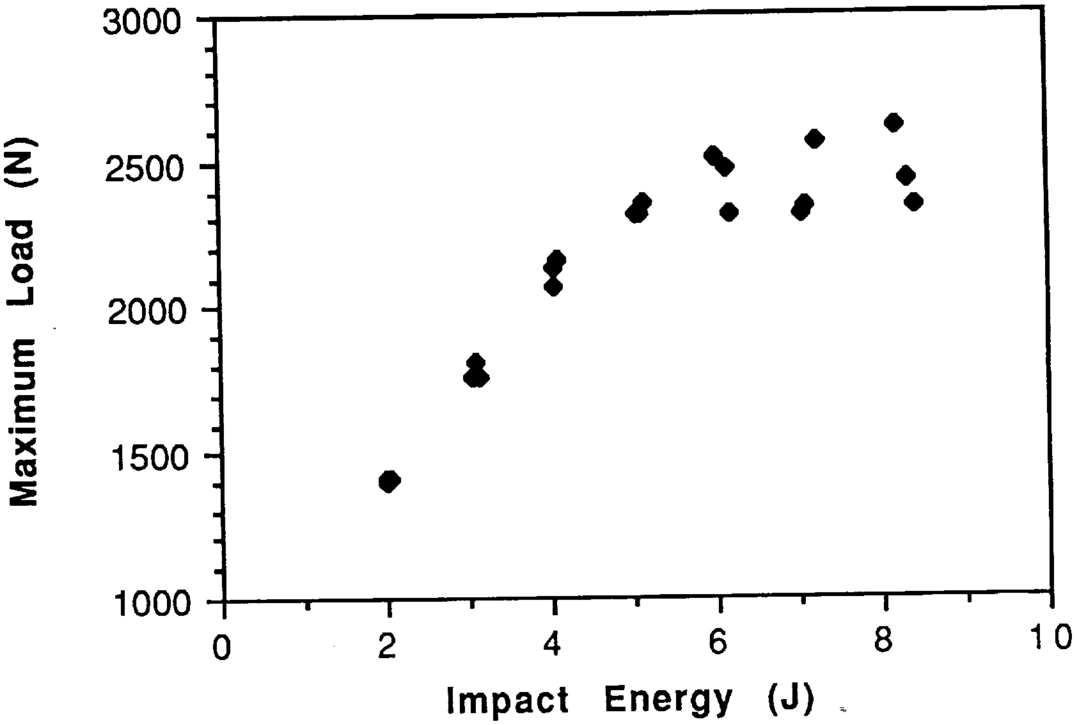


Figure 2. Maximum load versus impact energy for T300/948 without UHMWPE.

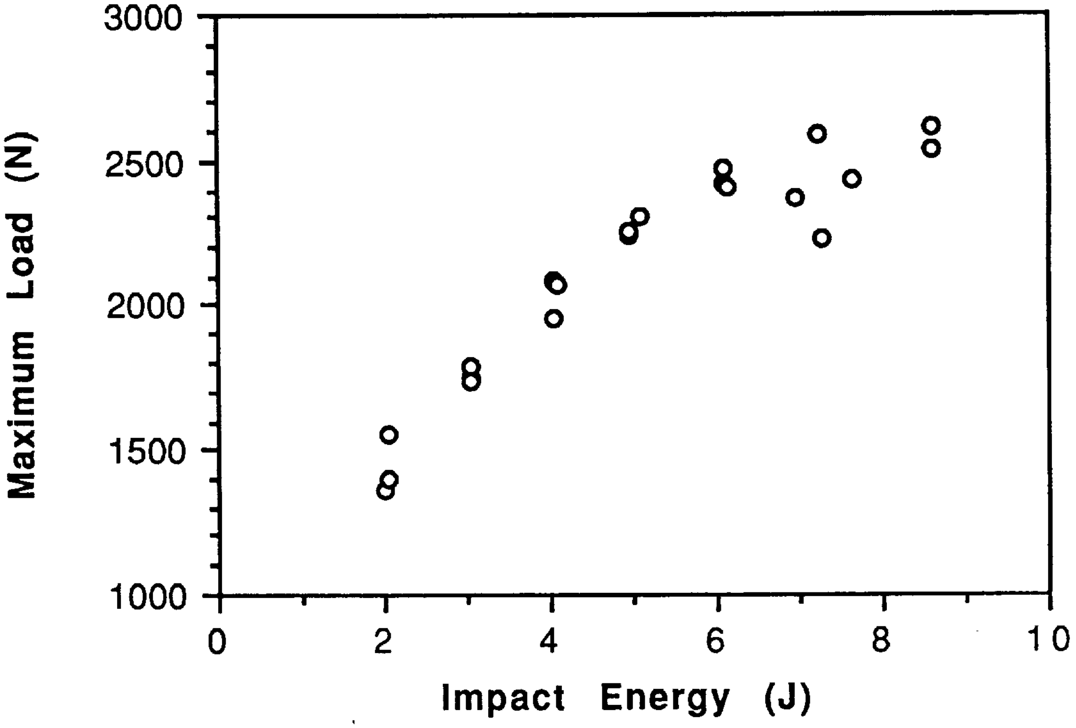


Figure 3. Maximum load versus impact energy for T300/948 with UHMWPE on top face.

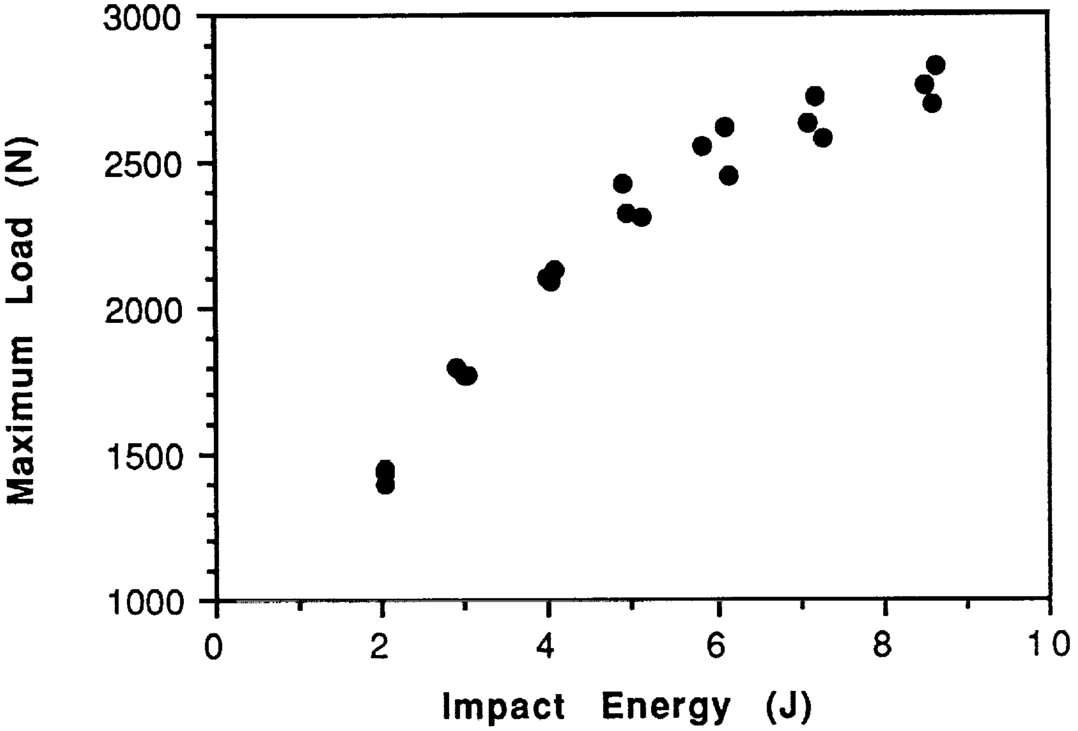


Figure 4. Maximum load versus impact energy for T300/948 with UHMWPE on bottom face.

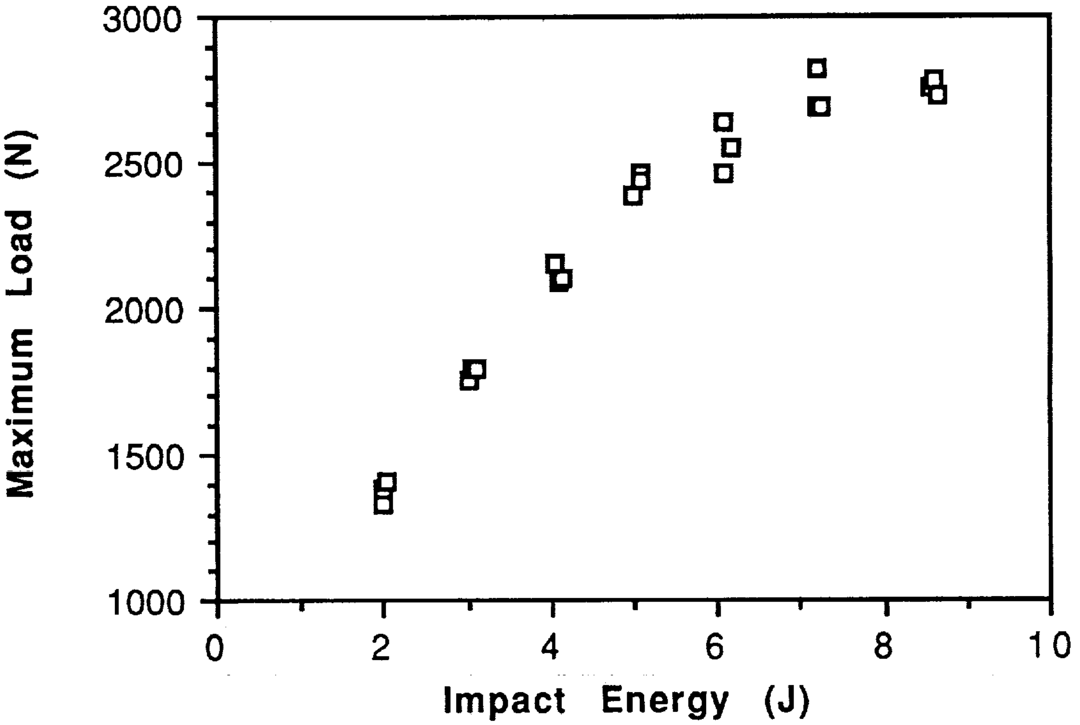


Figure 5. Maximum load versus impact energy for T300/948 with UHMWPE on both faces.

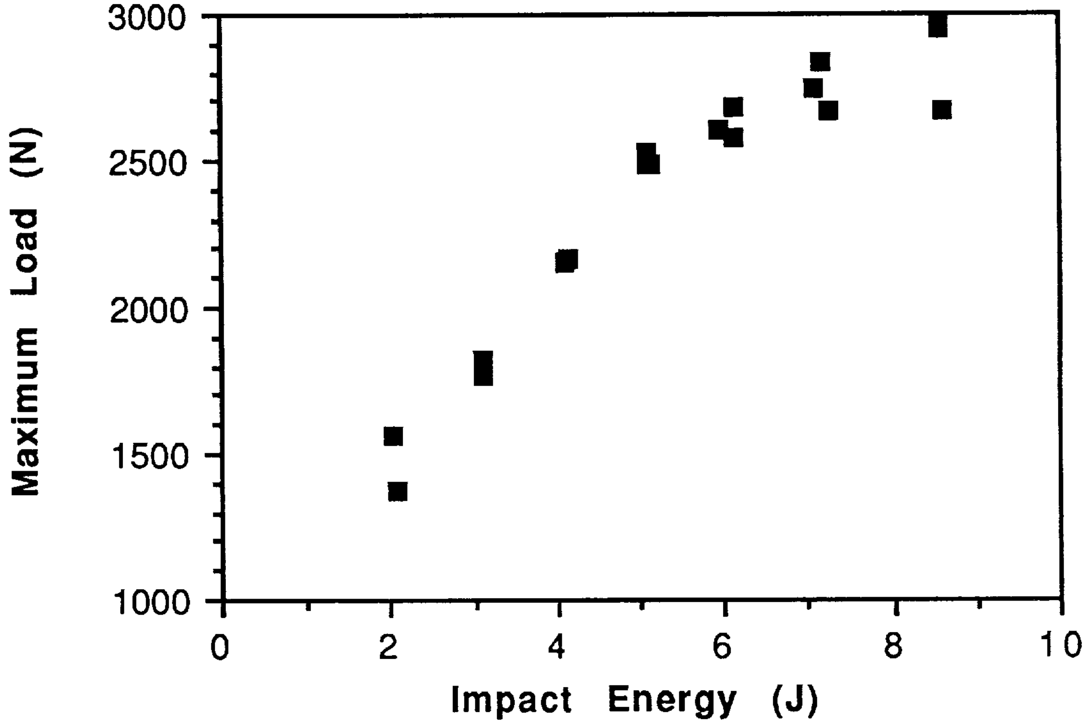


Figure 6. Maximum load versus impact energy for T300/948 with epoxy and UHMWPE on bottom face.

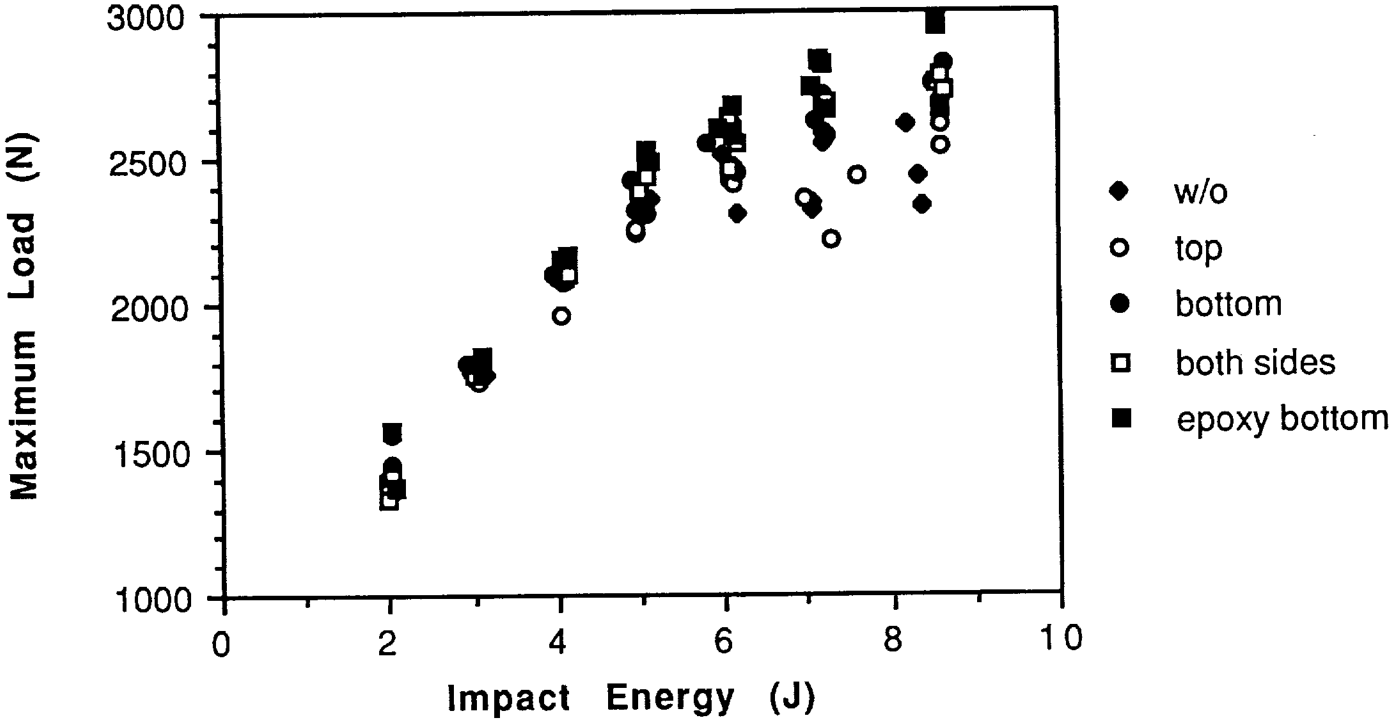


Figure 7. Maximum load versus impact energy for all configurations.

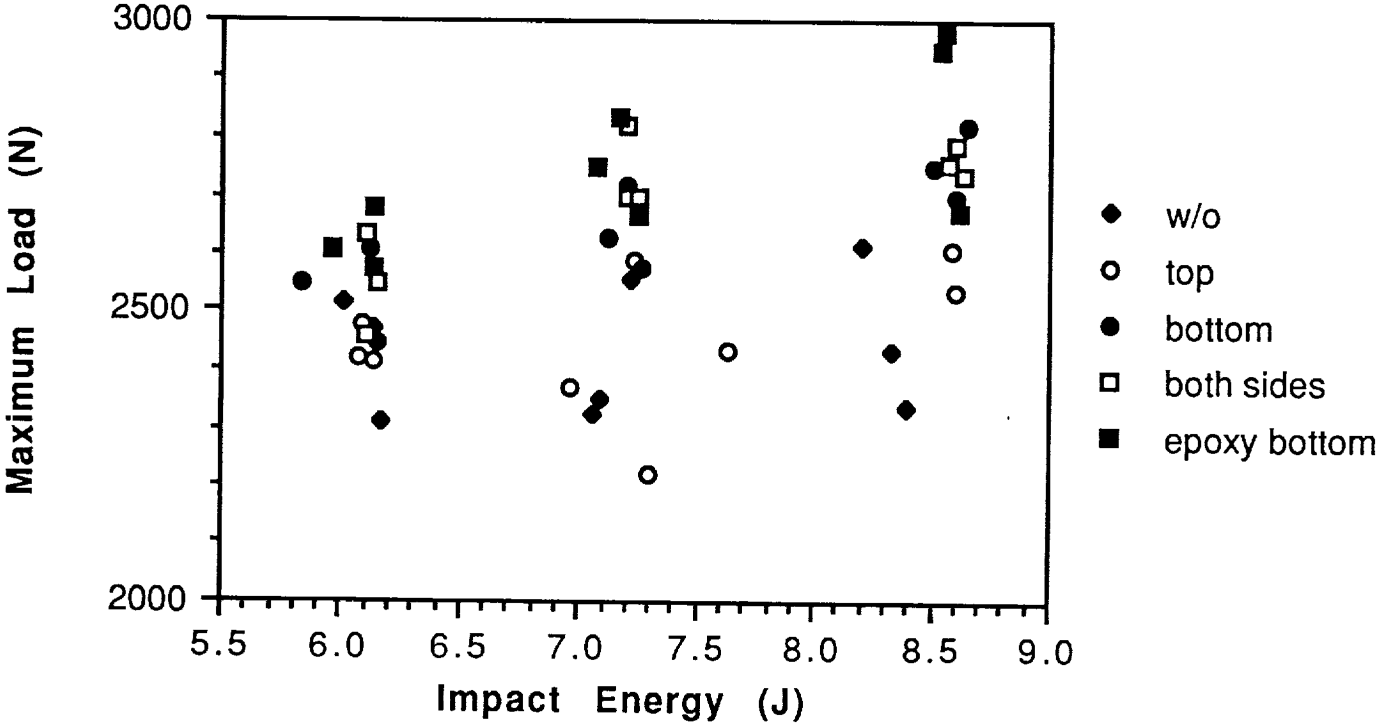


Figure 8. Maximum load versus impact energy for all configurations with magnified damage region.

The maximum energy level at which the specimens were impacted was approximately 8.5 J. At this energy level, clamped between plates with 7.62-cm diameter holes, the average length of a back surface crack varied according to the configuration of UHMWPE. The specimens without UHMWPE had 7.2-cm cracks. The panels with UHMWPE on top had 7.2-cm cracks. The samples with UHMWPE on bottom possessed 4.7-cm cracks. The plates with layers of UHMWPE on both sides had cracks measuring 4.4 cm. The specimens with UHMWPE attached on the bottom side by epoxy had 3.6-cm cracks.

D. Cross-Sectional Damage

After the cross-sectional cut was made to the specimens, the damage was examined and photographed. Photographs of selected specimens are provided in the appendix. A description of the internal damage to the composites is given below.

The T300/948 without UHMWPE showed slight matrix cracks at the 3.1-J impact. Delaminations were visible at the 4.1-J energy level. Much fiber breakage was evident within the specimen impacted at 7.1 J.

The T300/948 with UHMWPE on the top surface showed minor matrix cracking at the 3.0-J impact and delaminations at the 4.1-J impact. Partial fiber breakage was noticed at the 6.1-J and 7.2-J impacts with much fiber breakage occurring at the 8.5-J impacts.

The T300/948 with UHMWPE on the bottom surface and the T300/948 on both sides behaved similarly. They displayed delaminations and matrix cracking in the 4.9-J to 5.1-J range. Fiber breakage occurred for both configurations at the 8.5-J impact although the extent of the damage was less for the composite with UHMWPE on both surfaces.

The T300/948 with a layer of film epoxy and UHMWPE first sustained internal damage when delaminations and matrix cracks appeared with the 5.1-J impact. Partial fiber breakage was noticed after the 7.1-J and 8.5-J impacts.

E. Residual Compression Strength

Graphs were produced which plotted the initial energy of the impact with the compressive load to failure. Figure 9 compares the resultant CAI load of the damaged specimens with specimens that were not previously impacted. It shows that specimens damaged by an impact of approximately 6 J had between 36 and 47 percent less compressive strength values than the unimpacted samples. Figure 10 compares the residual compressive strength of the various UHMWPE configurations previously impacted at an energy between 5.9 J and 6.2 J. Surprisingly enough, although the UHMWPE improved the load withstood under foreign object impact, the panels with UHMWPE had a lower residual compression strength. The lower CAI strength could result from a larger region of smaller delaminations in the specimen that seems to occur as the Spectra prepreg distributes the load of the impactor over a larger surface area.

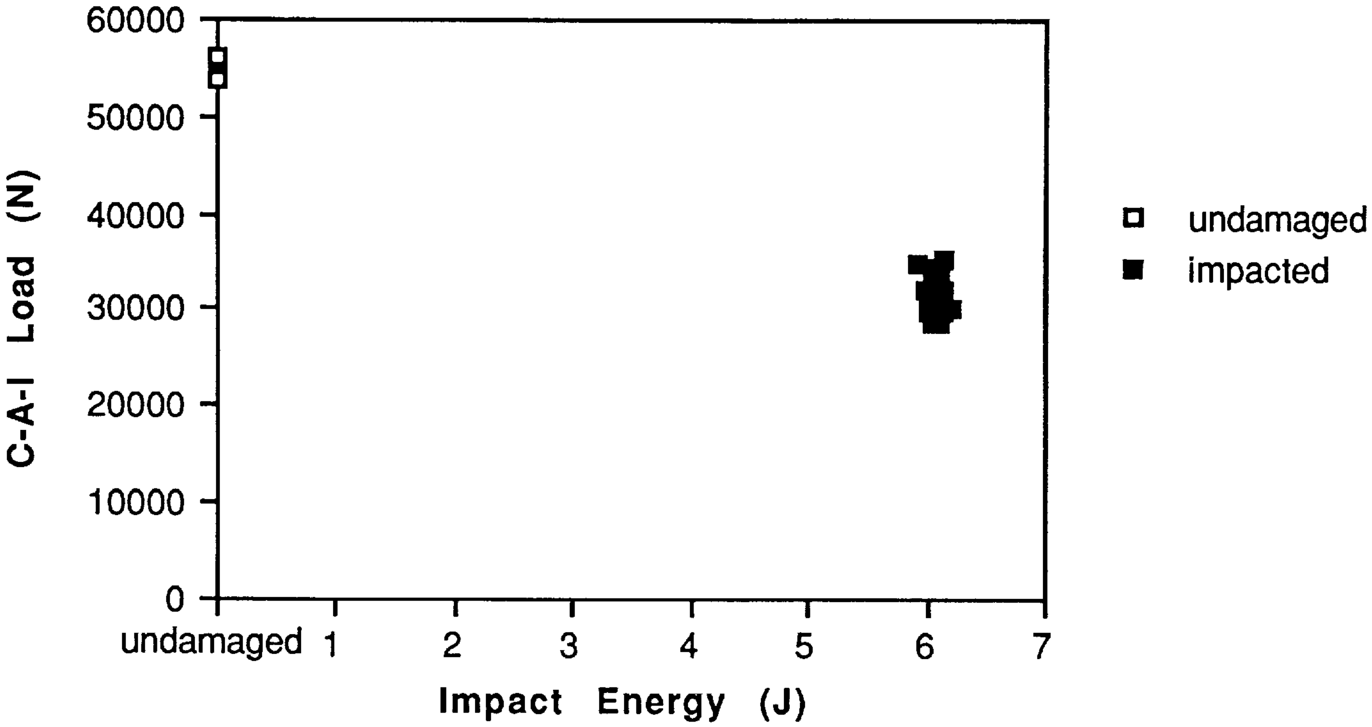


Figure 9. Compression-after-impact load to failure versus impact energy.

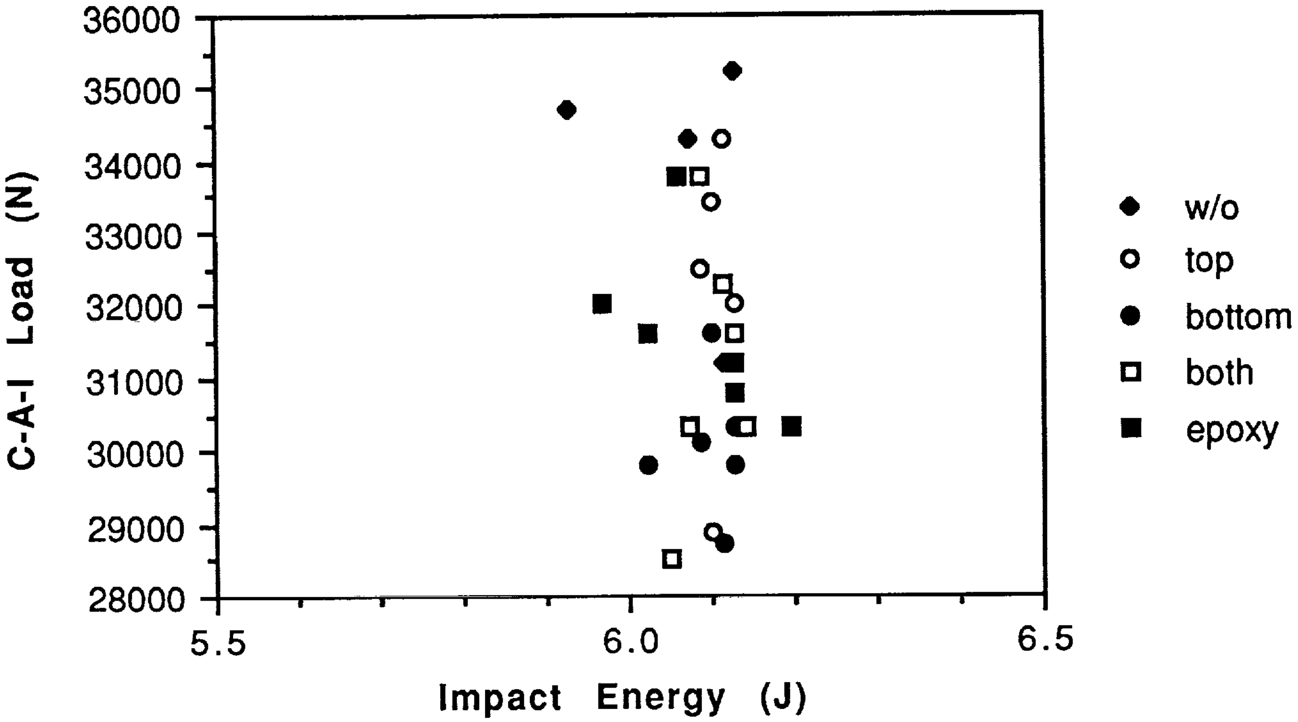


Figure 10. Compression-after-impact load to failure versus impact energy for damaged specimens.

IV. CONCLUSION

The purpose of this project was to study the ability of UHMWPE prepreg to enhance the damage tolerance characteristics of composites when bonded to these composites as hybrids. For the composite panels and the hybrids with Spectra on the impacted side, nonimpacted side, or both sides, the following conclusions can be made:

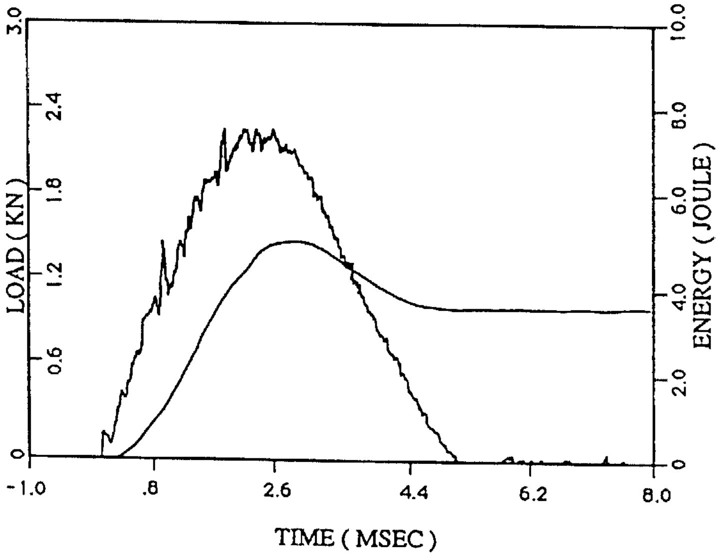
1. Cross-sectioning through the damage region shows no significant differences in the visual damage sustained by the various specimens when hit at similar impact energies.

2. Graphs plotting maximum load against impact energy indicate that specimens with UHMWPE on the nonimpacted surface could withstand slightly higher loads than specimens with UHMWPE on the impacted side. These graphs show that the samples with Spectra bonded by epoxy to the nonimpacted surface withstood an approximately 20 percent higher load before fiber breakage.

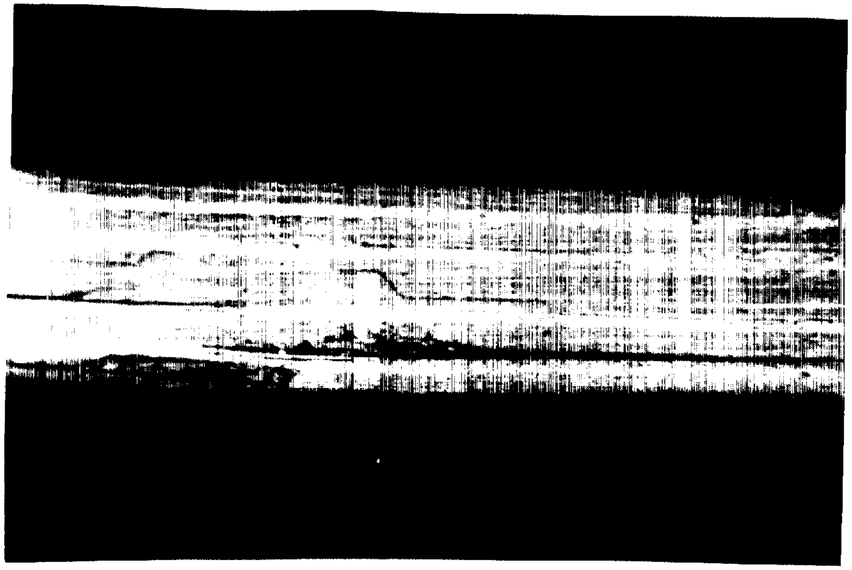
3. The residual strength seems to be adversely affected by the presence of UHMWPE. Although the differences were extremely small, the hybrid composites had compression-after-impact strengths that were slightly lower than the T300/048 panels without Spectra. It is speculated that this is due to the dissipation of load over a larger surface area when Spectra is present, resulting in a larger damage zone. A study into this phenomenon is currently underway and the results will be published at a later date.

APPENDIX

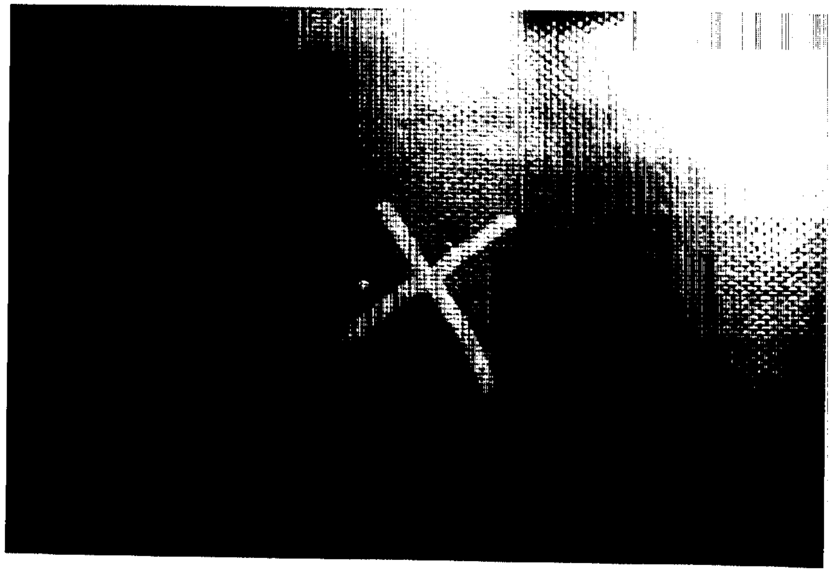
Instrumented Output, Cross-Sectional Photographs, and Surface Photographs for Each Configuration



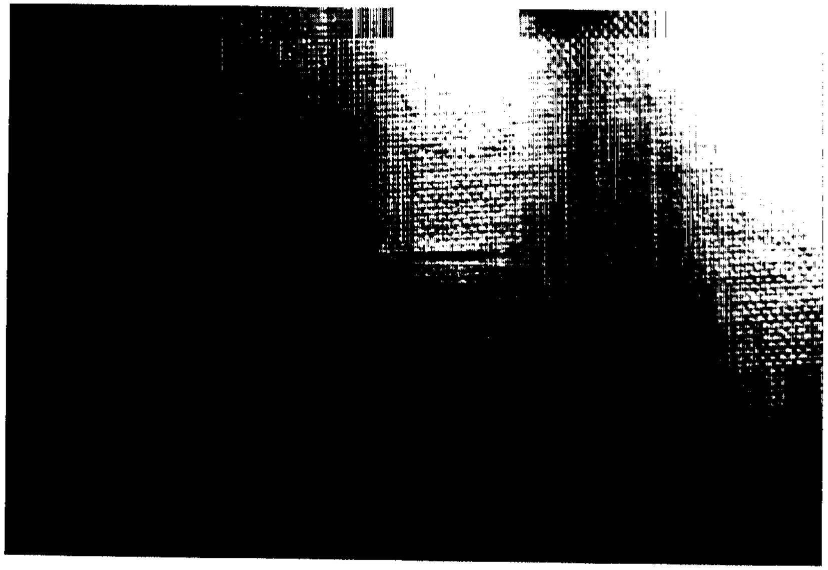
INSTRUMENTED OUTPUT



CROSS SECTION

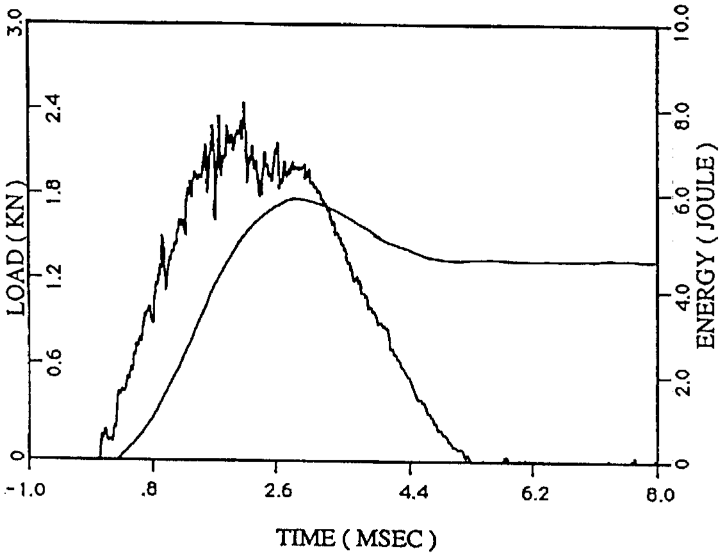


FRONT

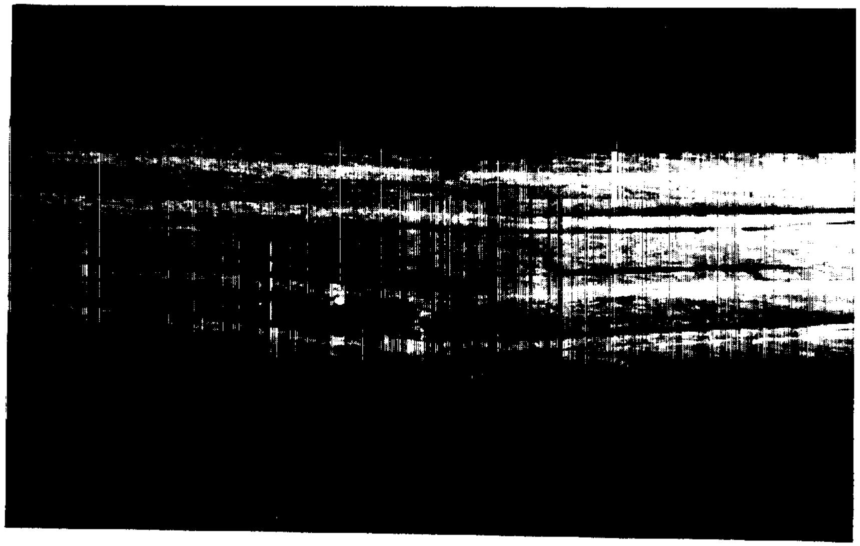


BACK

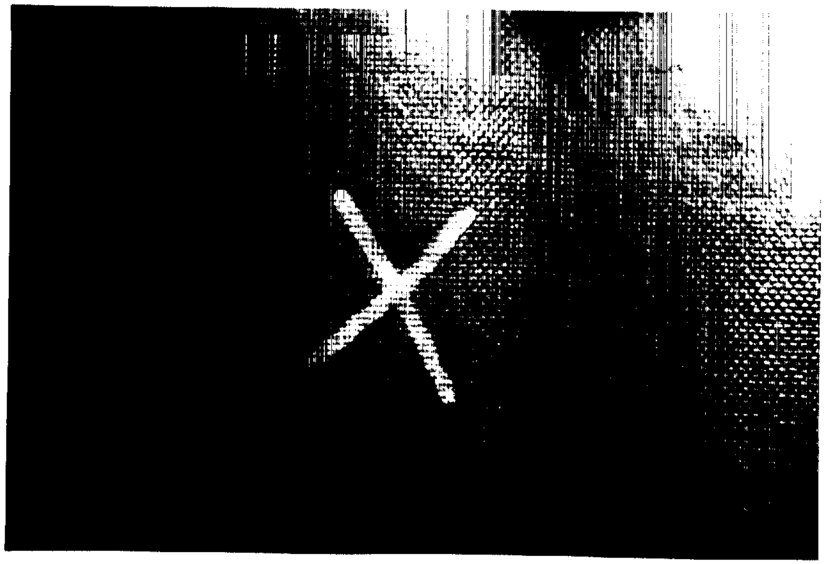
WITHOUT SPECTRA IMPACT ENERGY 5 J



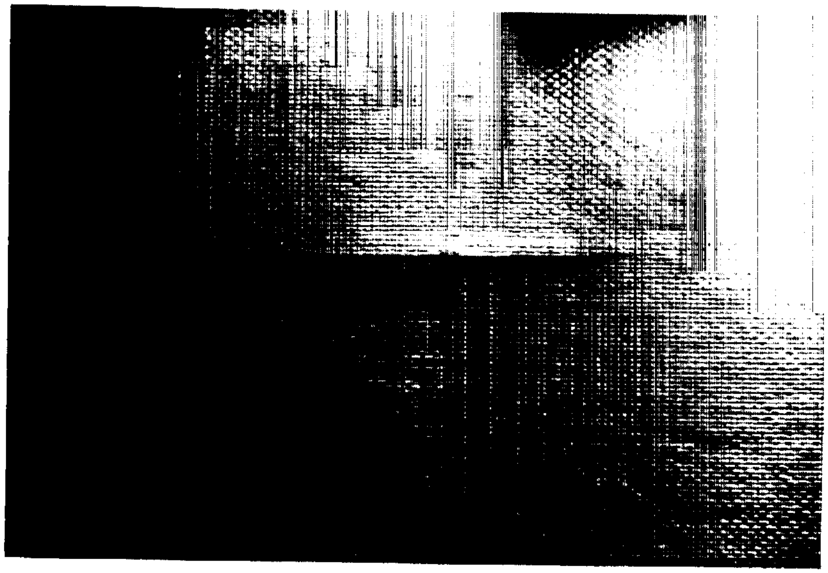
INSTRUMENTED OUTPUT



CROSS SECTION

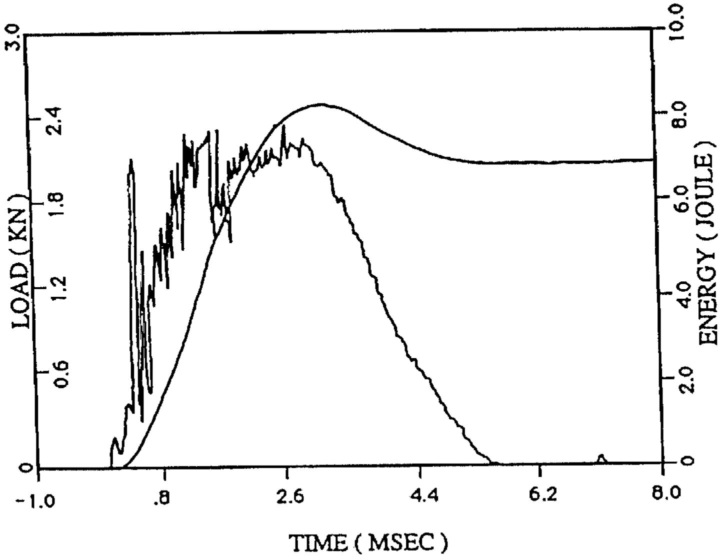


FRONT

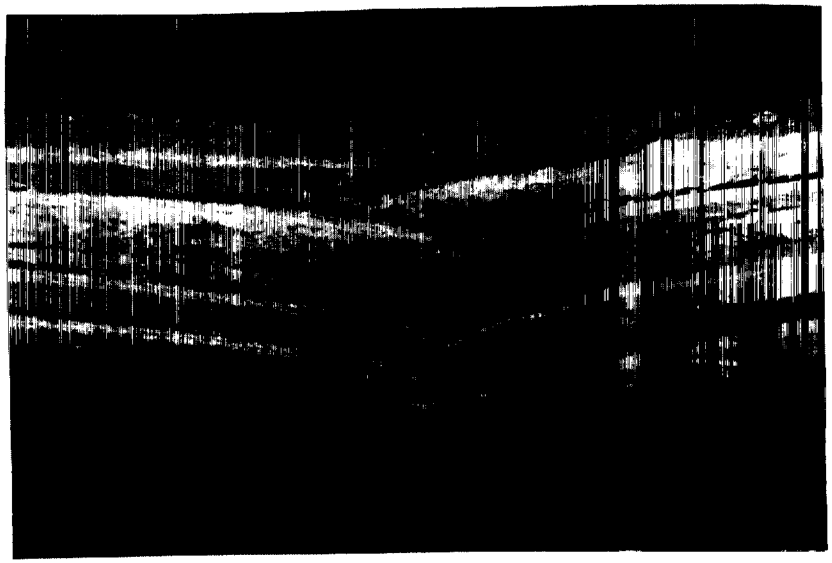


BACK

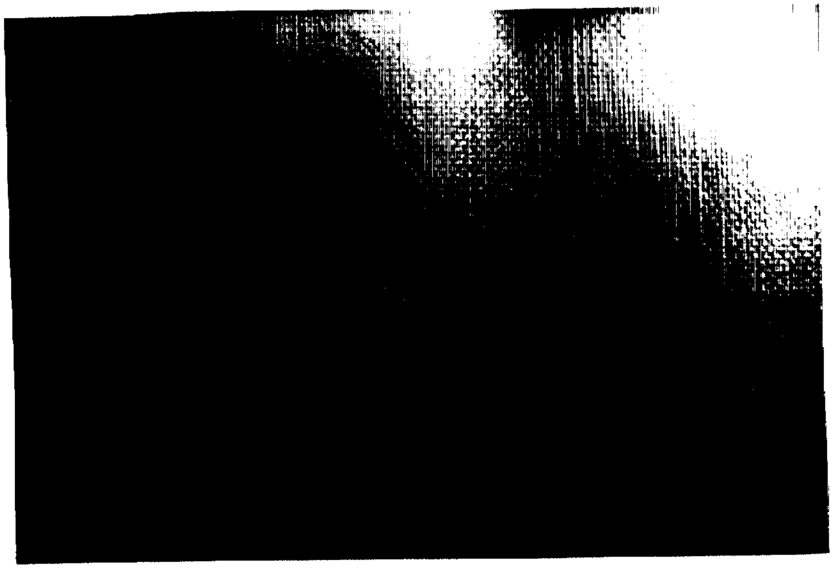
WITHOUT SPECTRA   IMPACT ENERGY 6 J



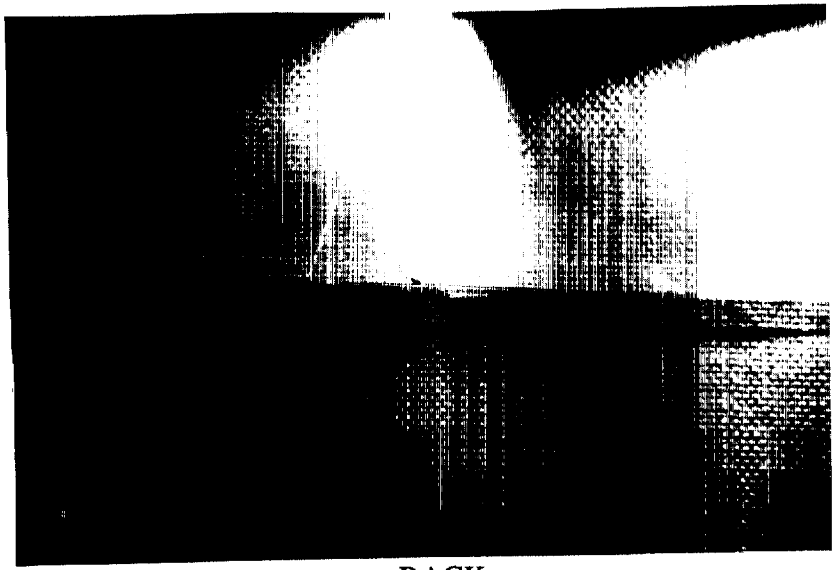
INSTRUMENTED OUTPUT



CROSS SECTION

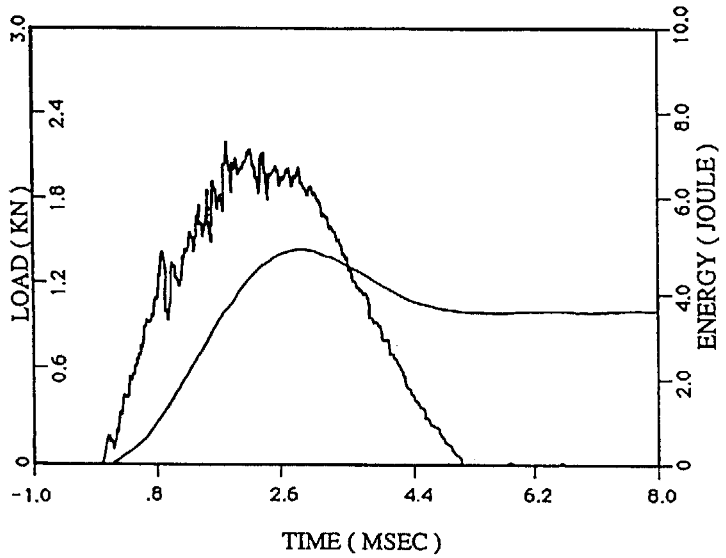


FRONT



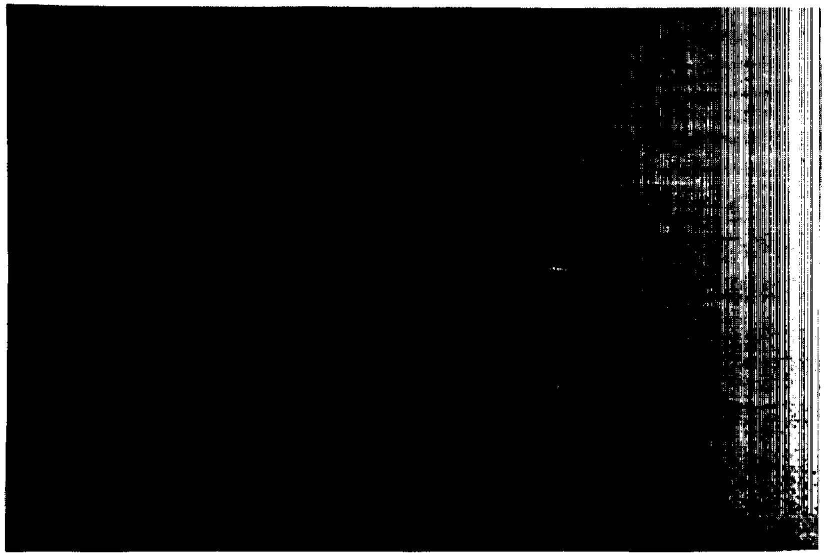
BACK

WITHOUT SPECTRA   IMPACT ENERGY 8.5 J

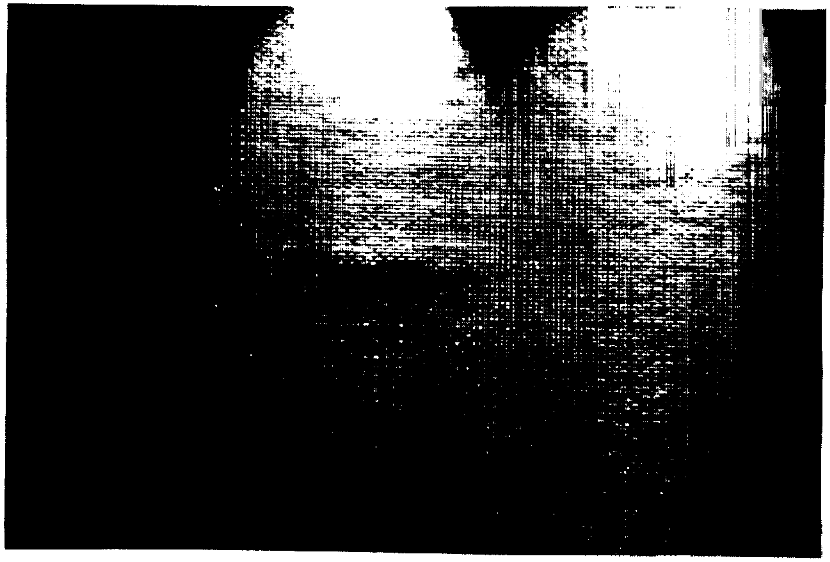


INSTRUMENTED OUTPUT

CROSS SECTION

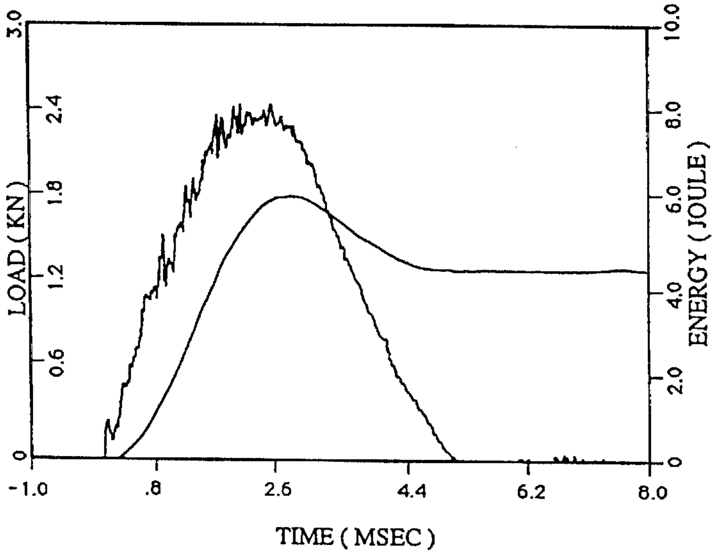


FRONT

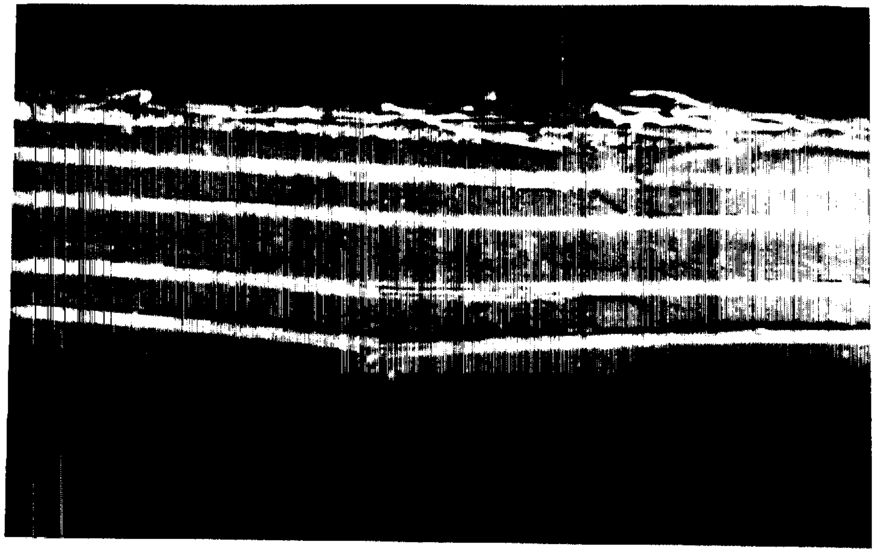


BACK

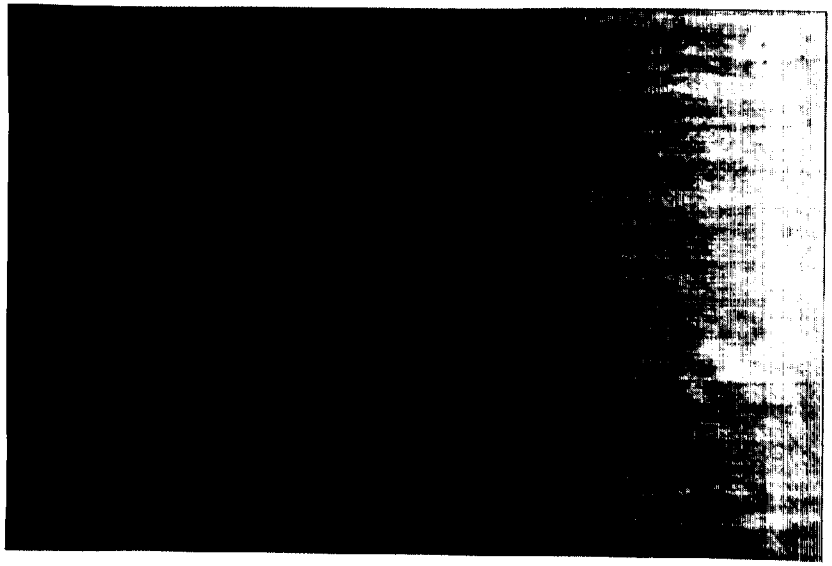
SPECTRA ON TOP   IMPACT ENERGY 5 J



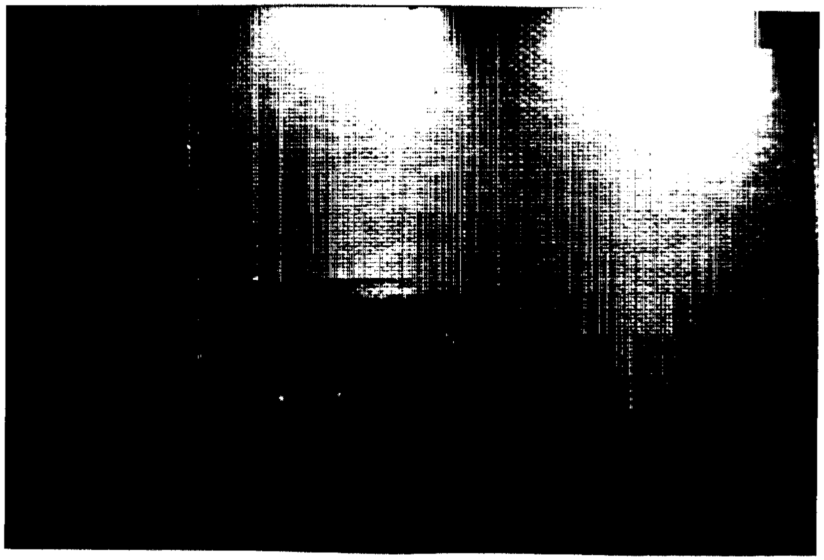
INSTRUMENTED OUTPUT



CROSS SECTION

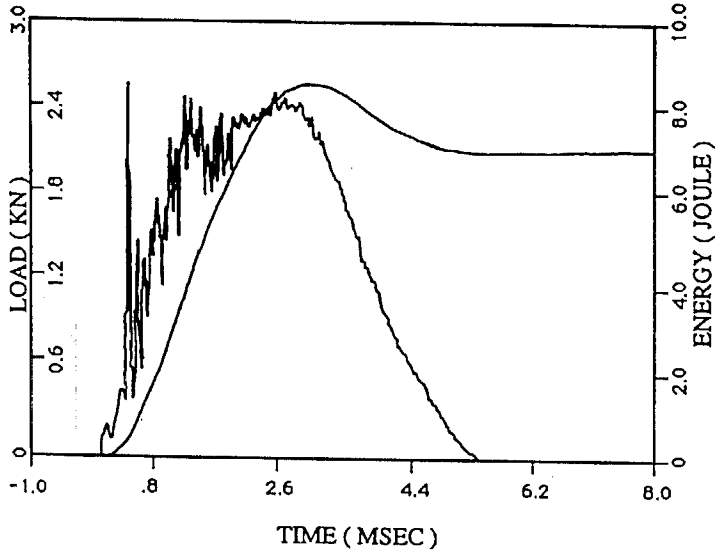


FRONT

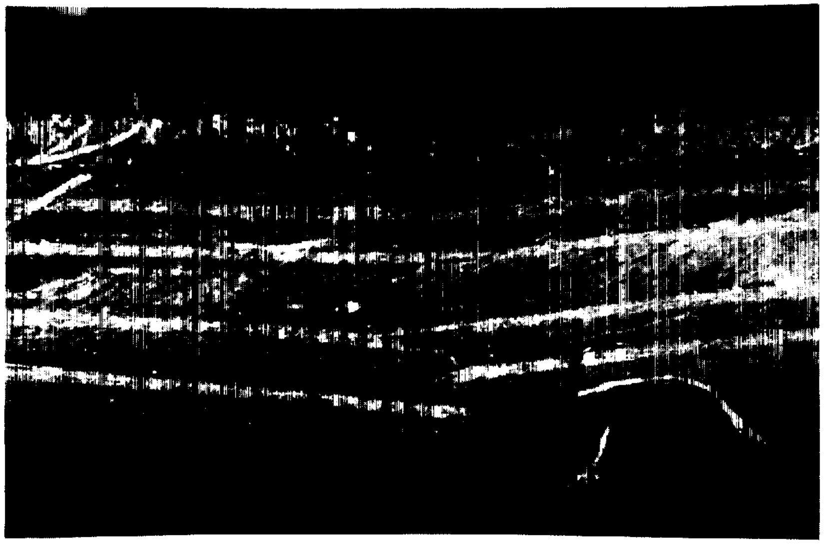


BACK

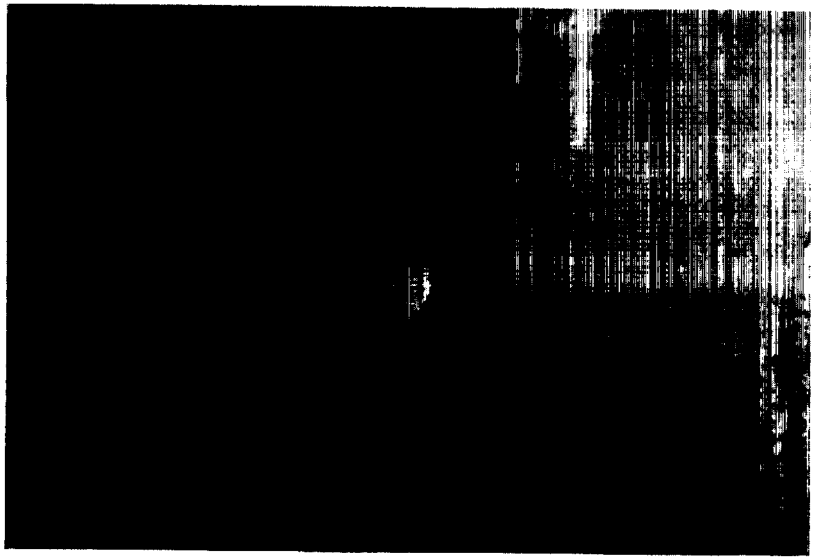
SPECTRA ON TOP   IMPACT ENERGY 6 J



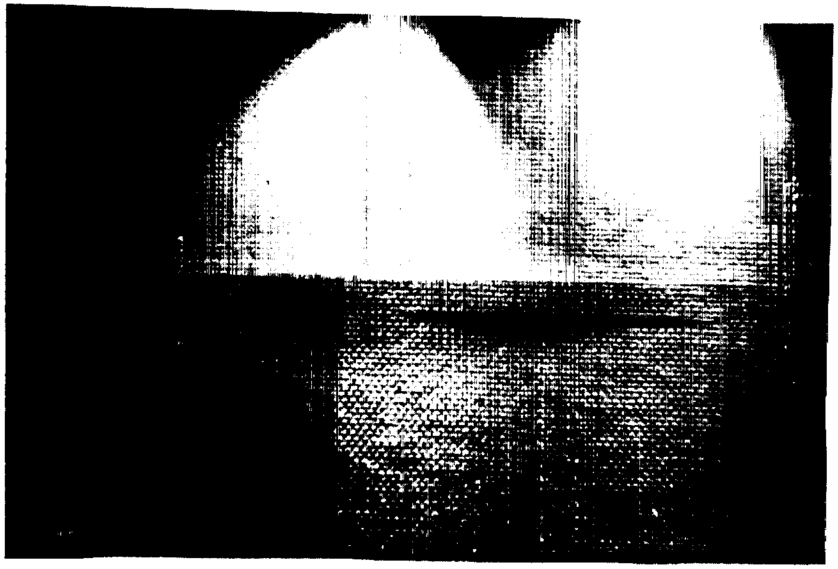
INSTRUMENTED OUTPUT



CROSS SECTION

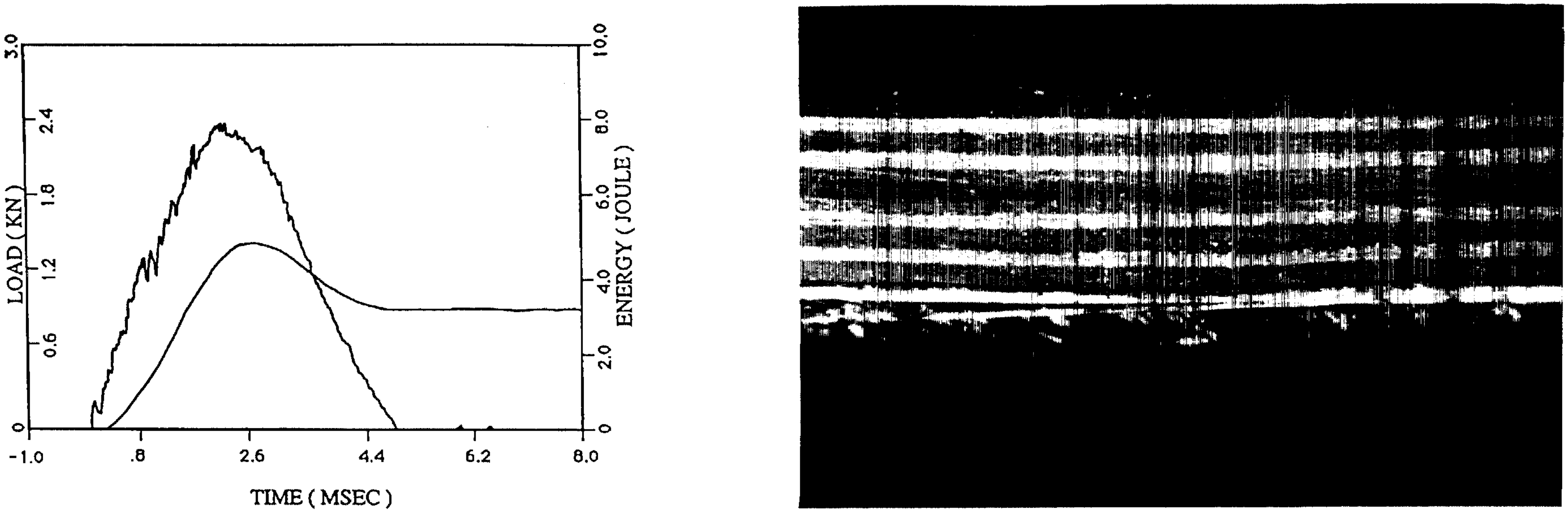


FRONT



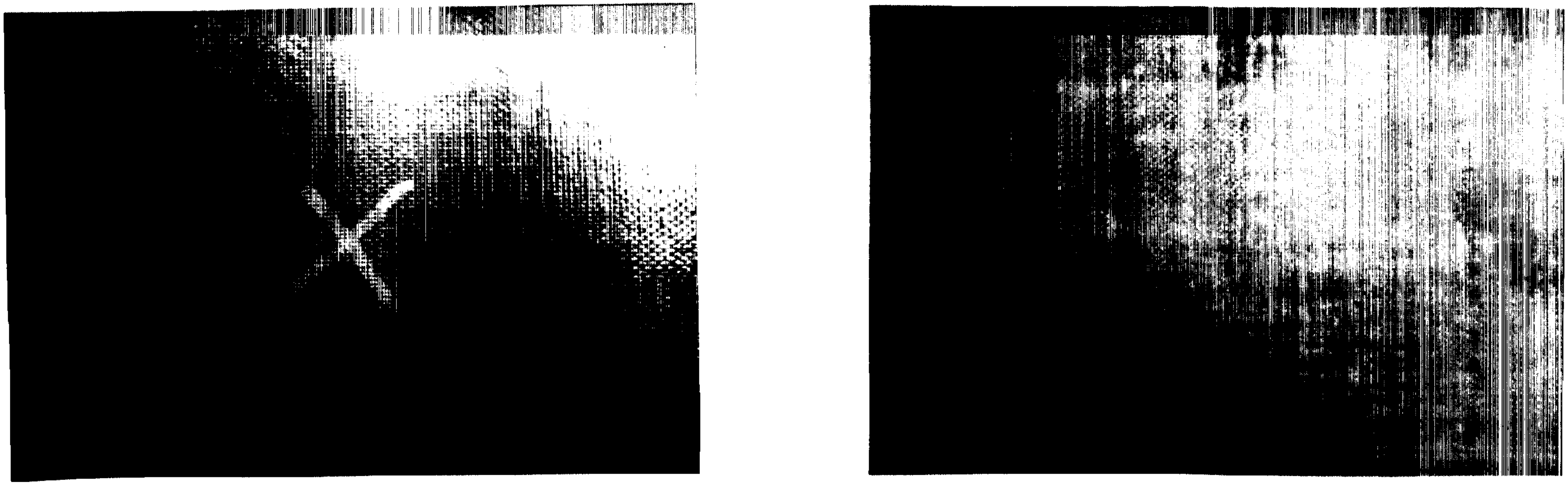
BACK

SPECTRA ON TOP IMPACT ENERGY 8.5 J



INSTRUMENTED OUTPUT

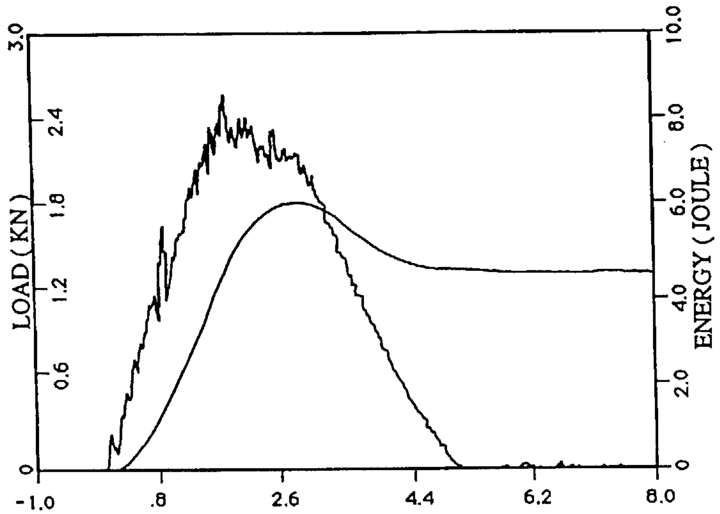
CROSS SECTION



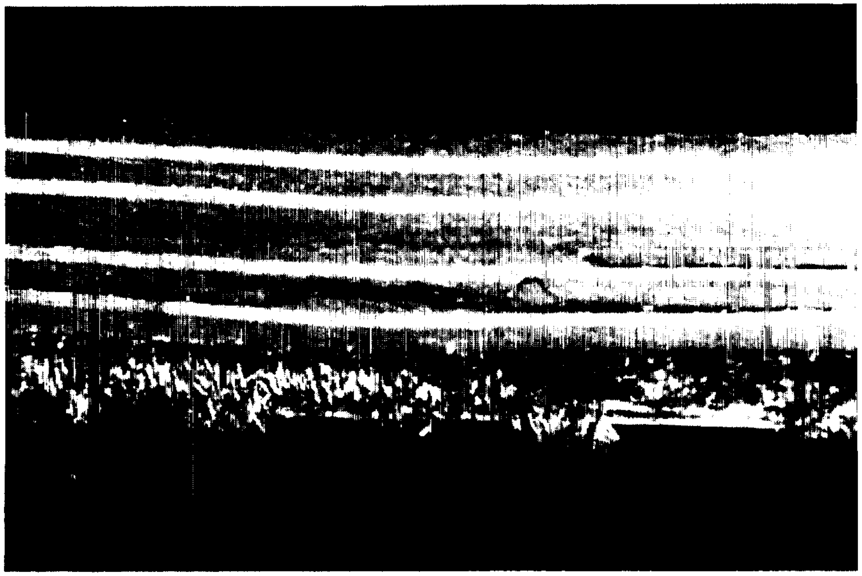
FRONT

BACK

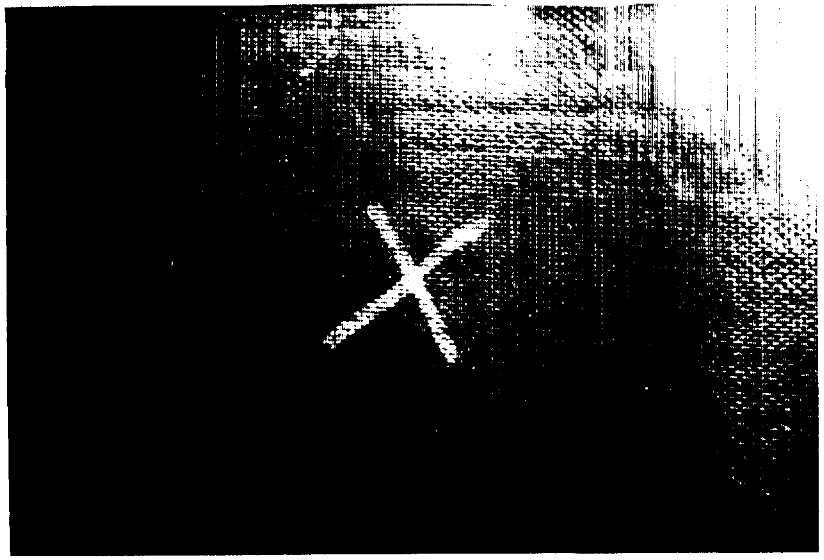
SPECTRA ON BOTTOM IMPACT ENERGY 5 J



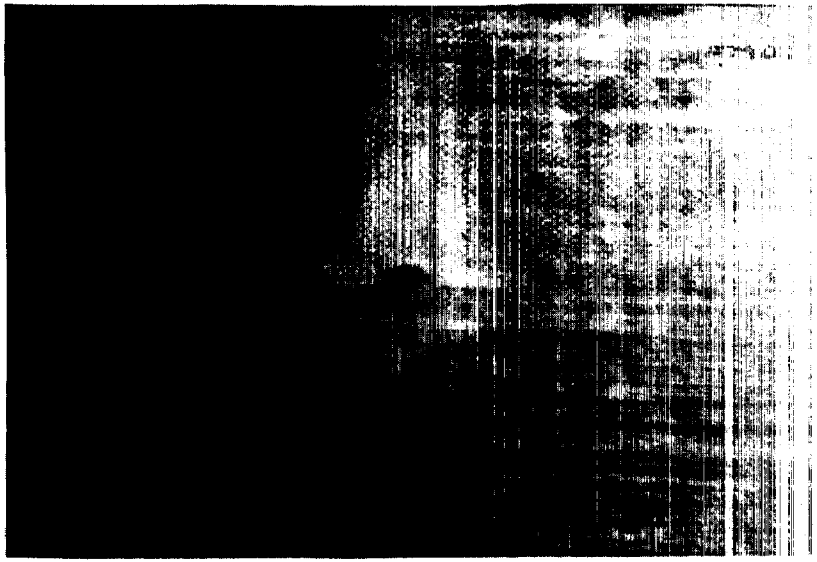
INSTRUMENTED OUTPUT



CROSS SECTION

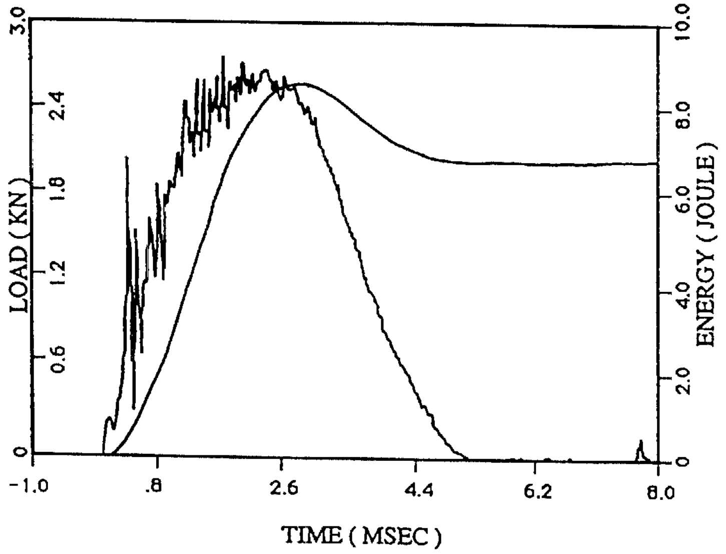


FRONT

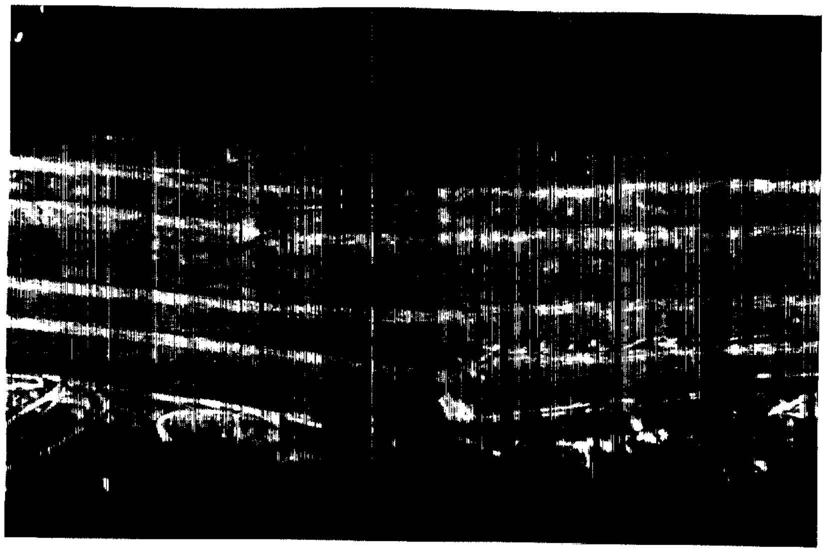


BACK

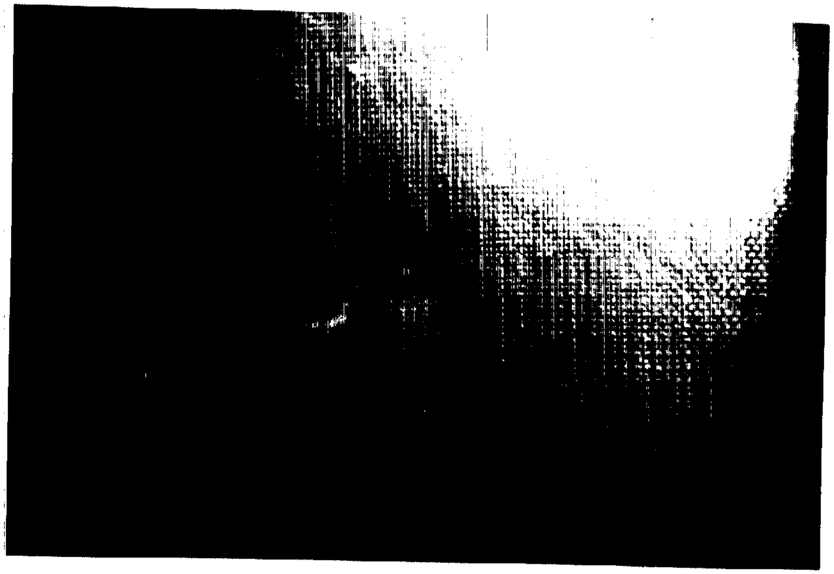
SPECTRA ON BOTTOM IMPACT ENERGY 6 J



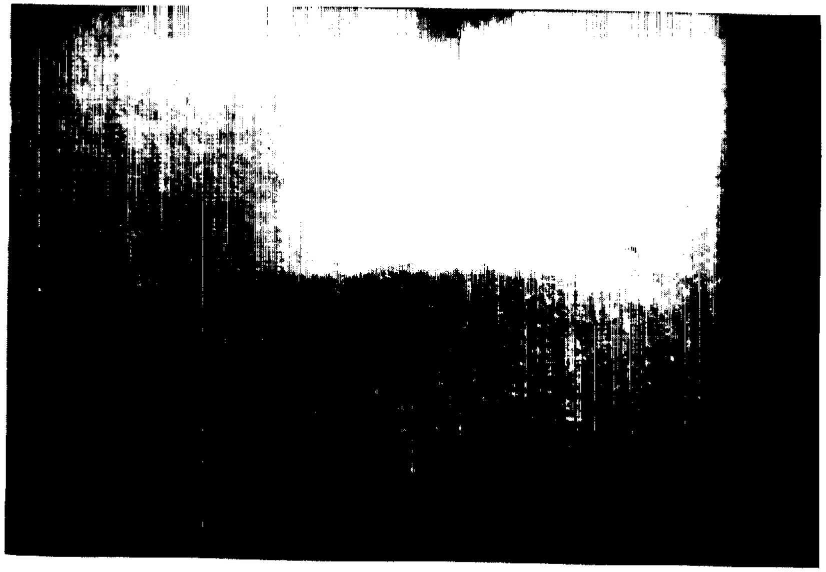
INSTRUMENTED OUTPUT



CROSS SECTION

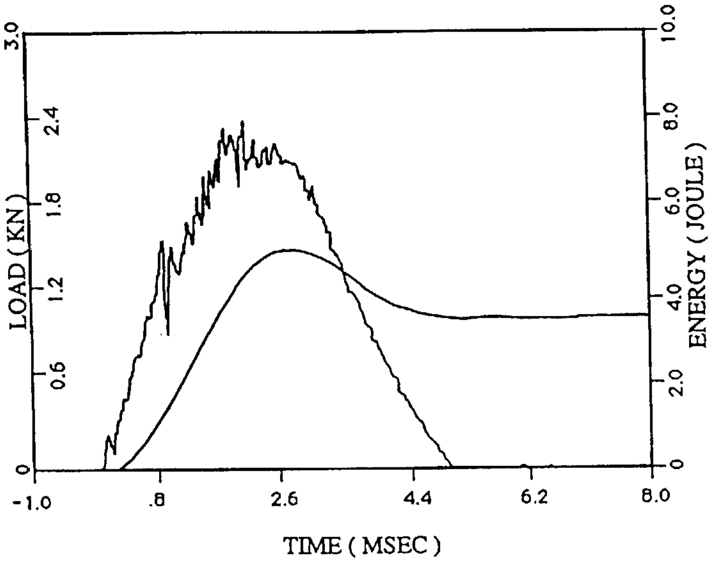


FRONT

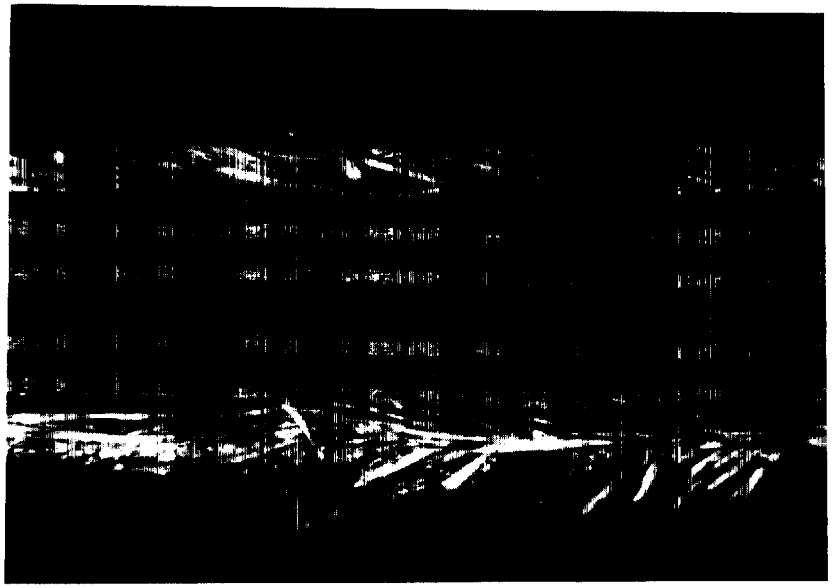


BACK

SPECTRA ON BOTTOM IMPACT ENERGY 8.5 J

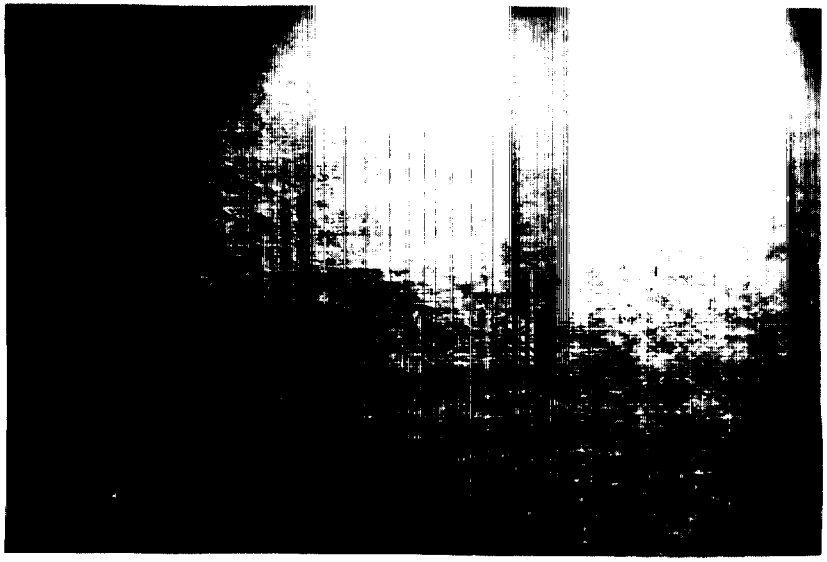


INSTRUMENTED OUTPUT



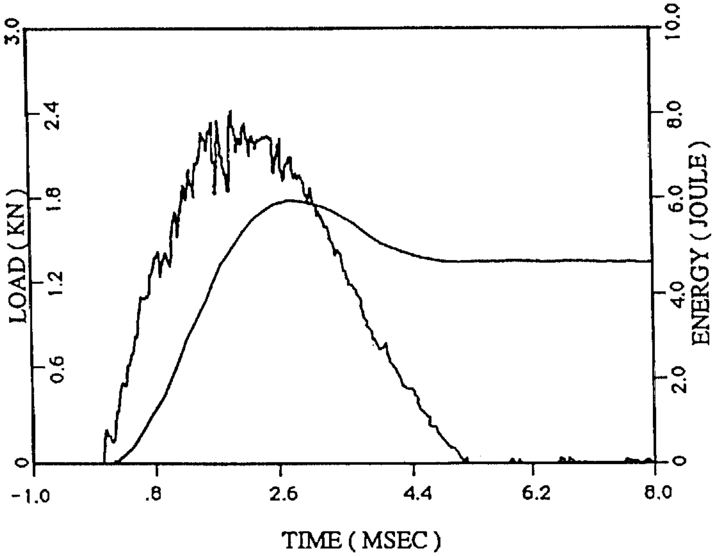
CROSS SECTION

FRONT

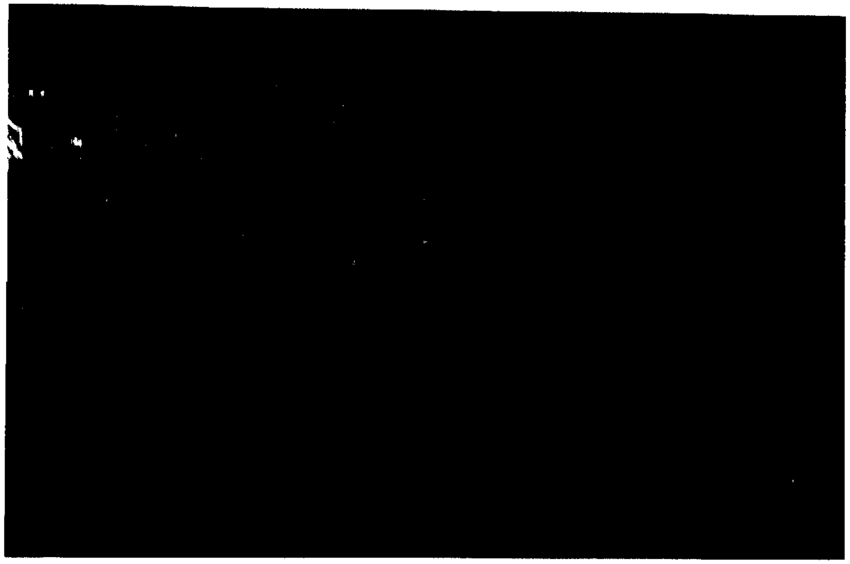


BACK

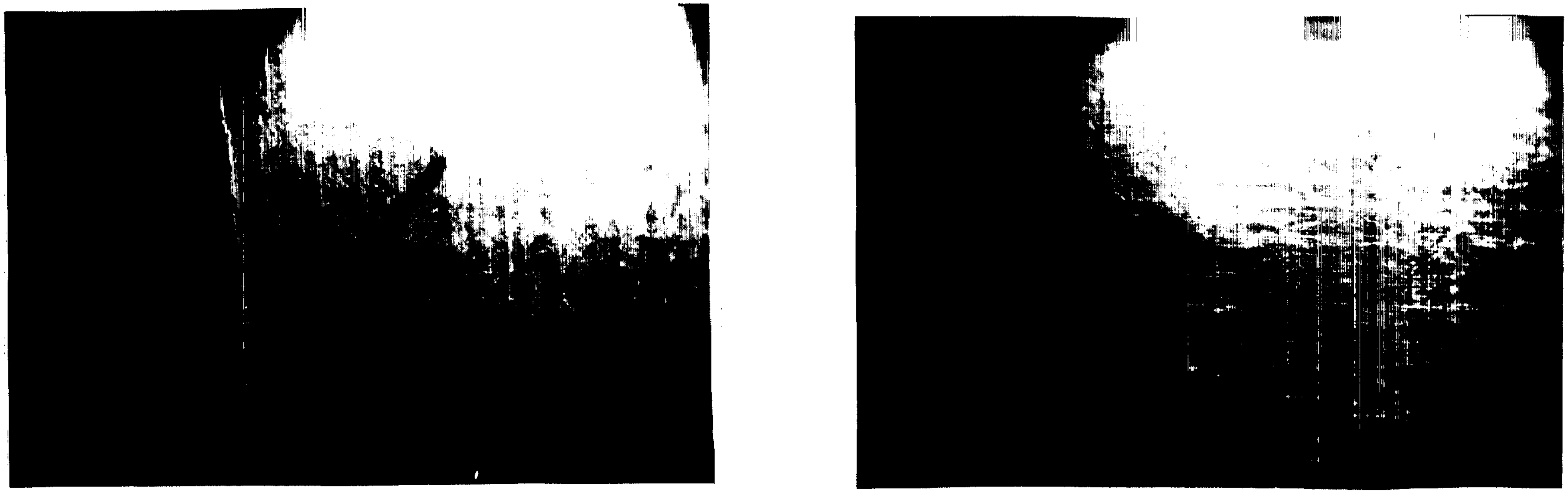
SPECTRA ON BOTH IMPACT ENERGY 5 J



INSTRUMENTED OUTPUT



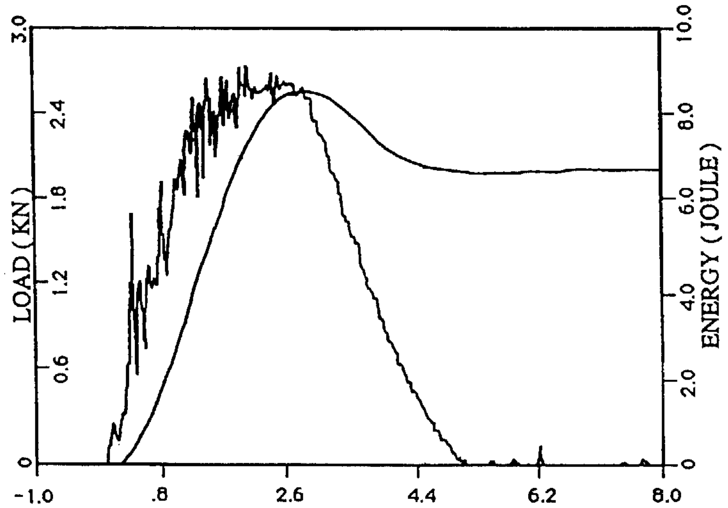
CROSS SECTION



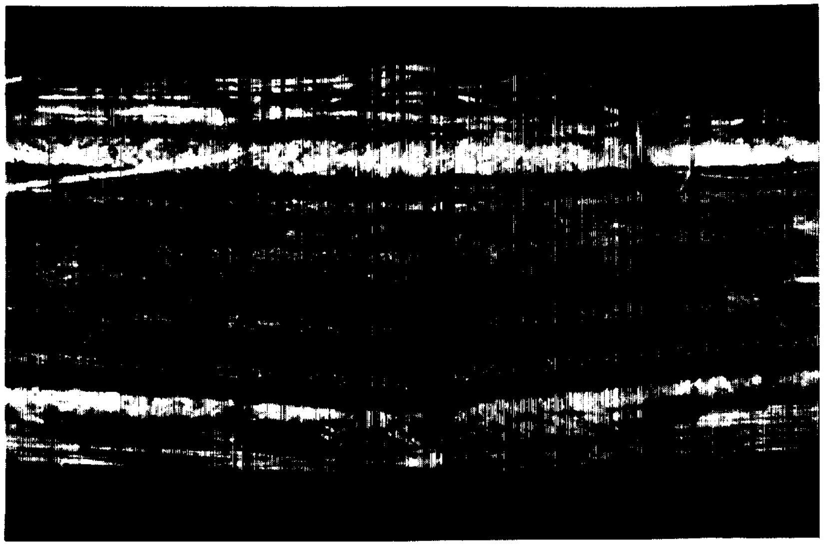
FRONT

BACK

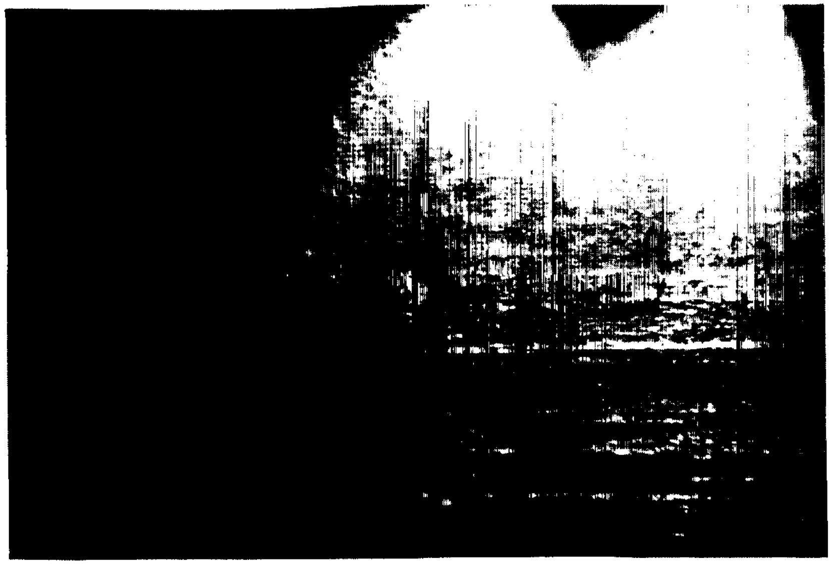
SPECTRA ON BOTH IMPACT ENERGY 6 J



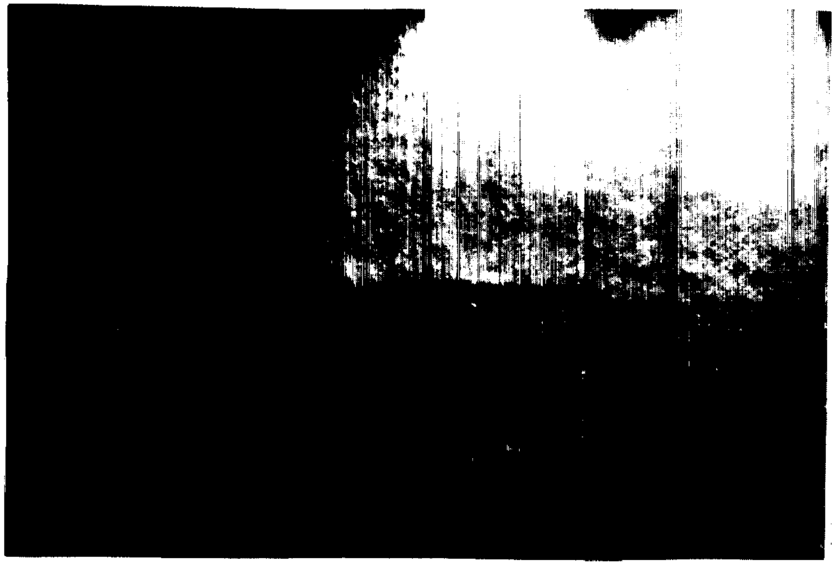
INSTRUMENTED OUTPUT



CROSS SECTION

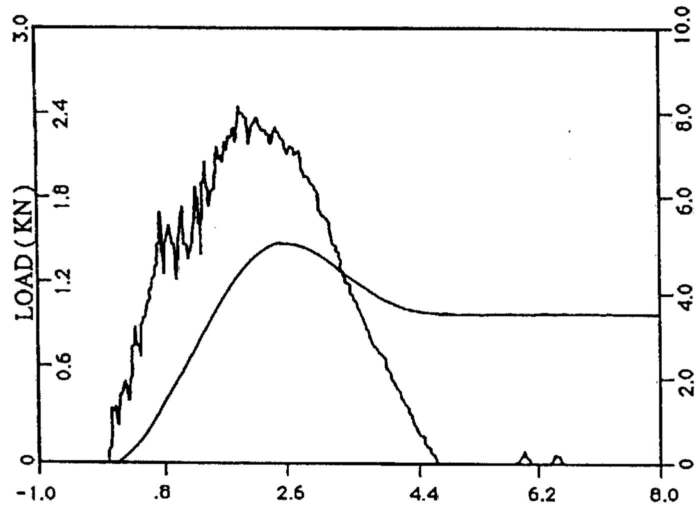


FRONT

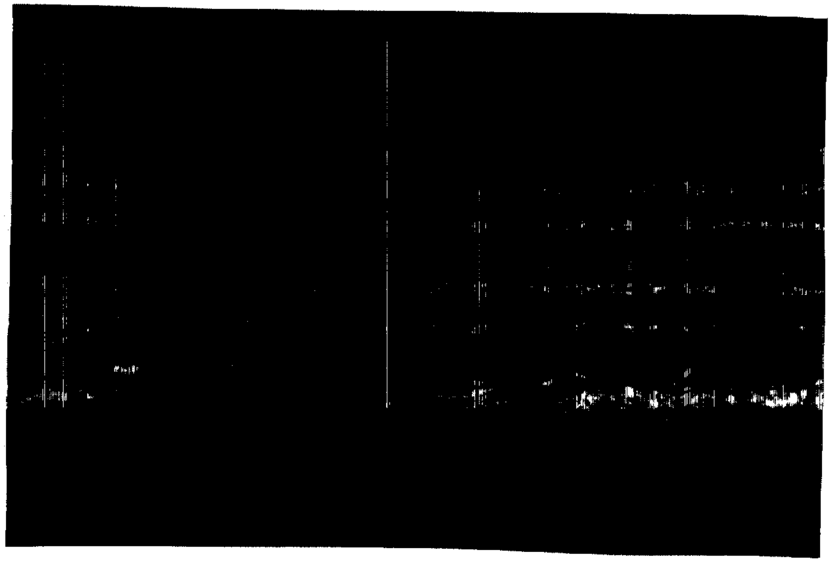


BACK

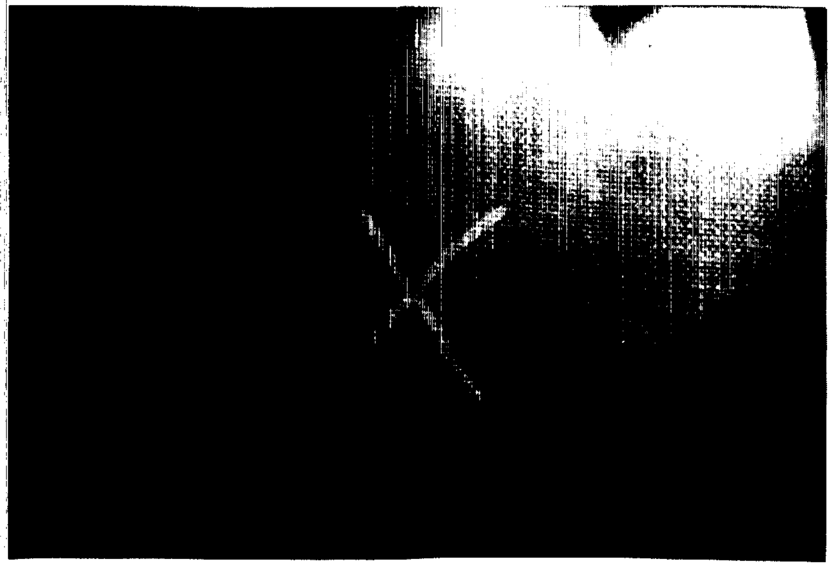
SPECTRA ON BOTH IMPACT ENERGY 8.5 J



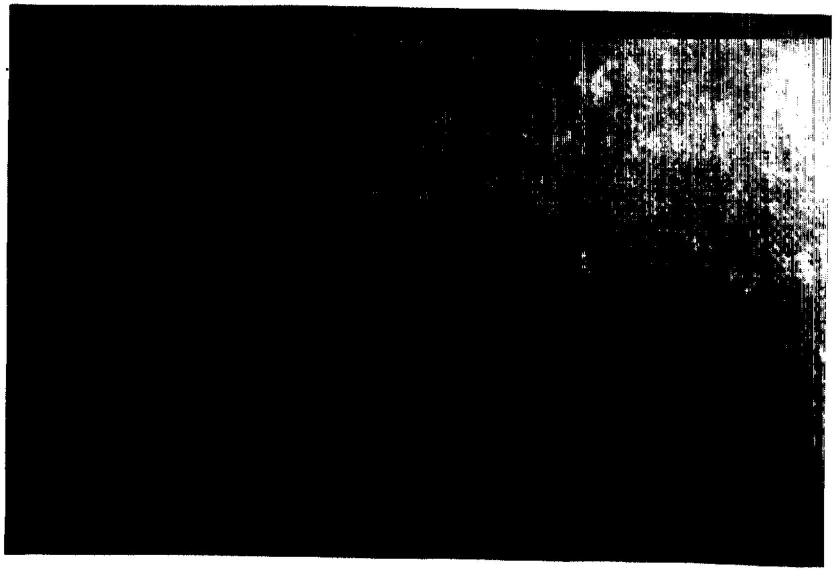
INSTRUMENTED OUTPUT



CROSS SECTION

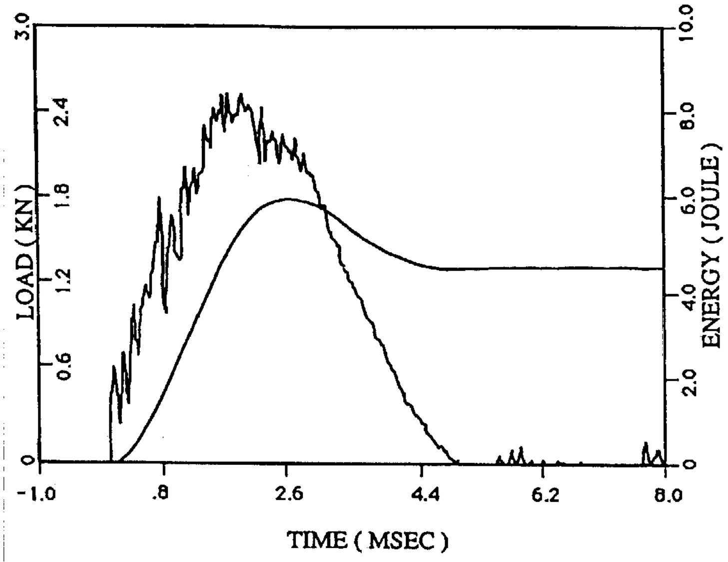


FRONT

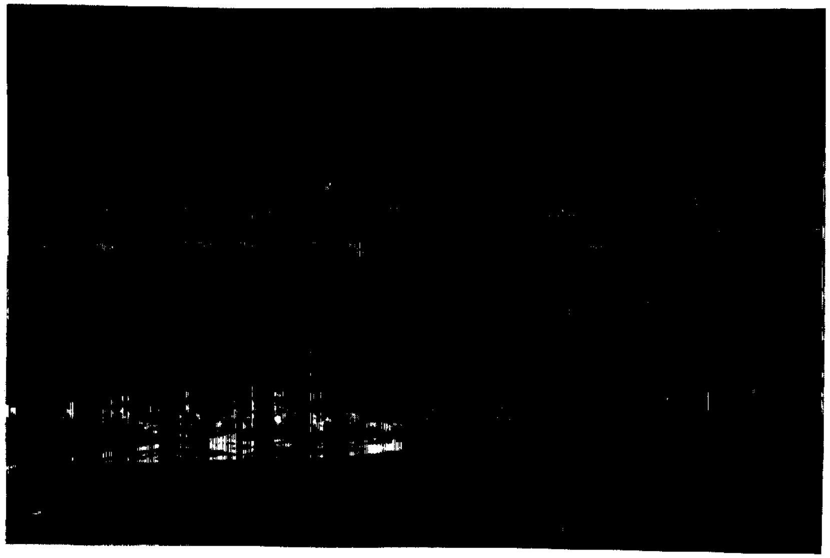


BACK

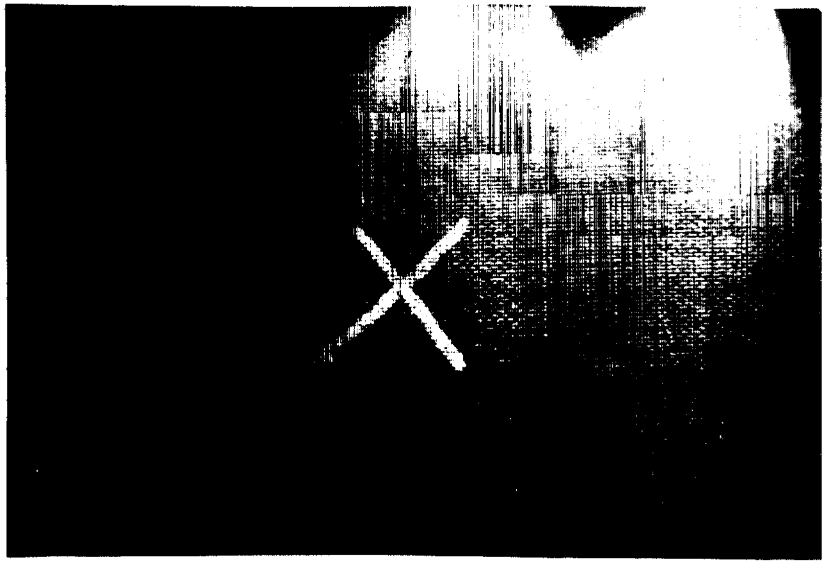
SPECTRA WITH EPOXY IMPACT ENERGY 5 J



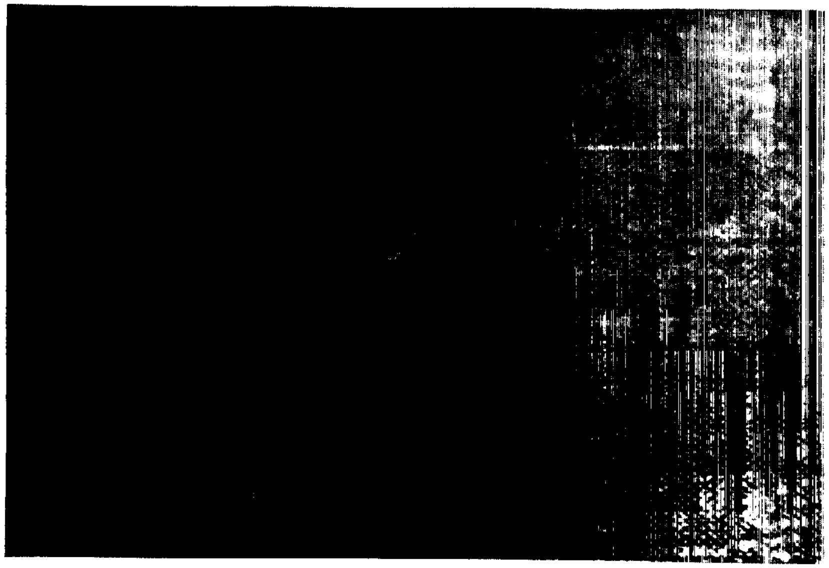
INSTRUMENTED OUTPUT



CROSS SECTION

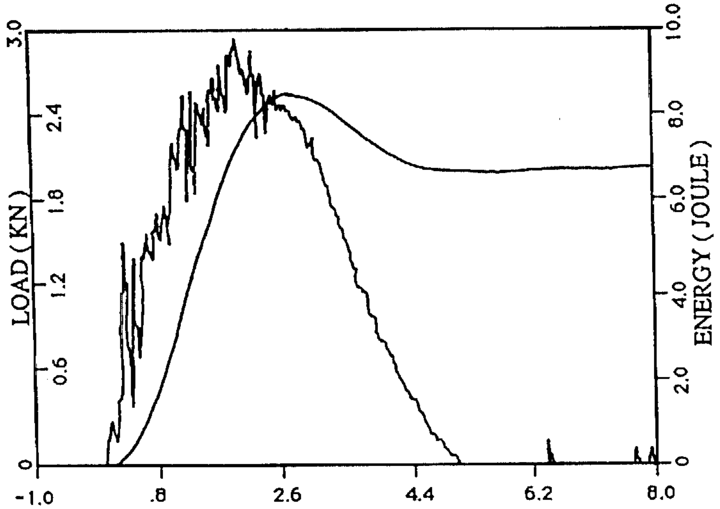


FRONT

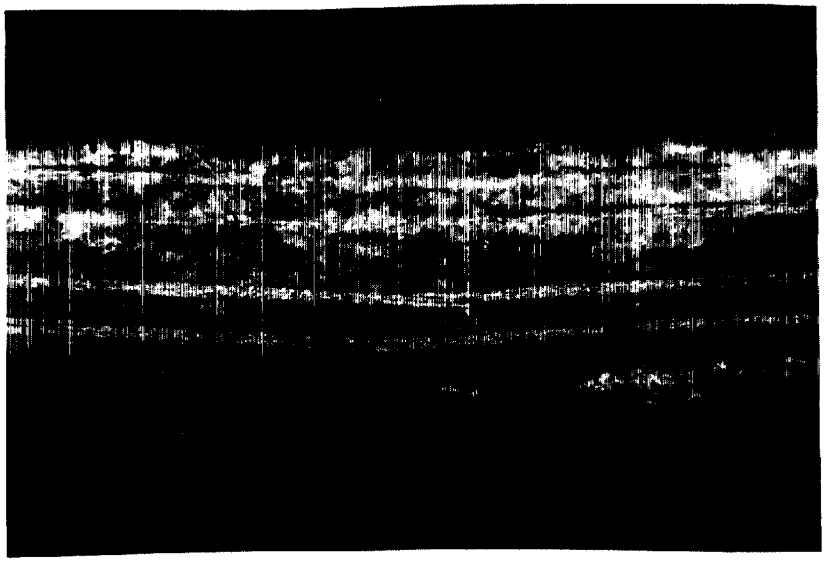


BACK

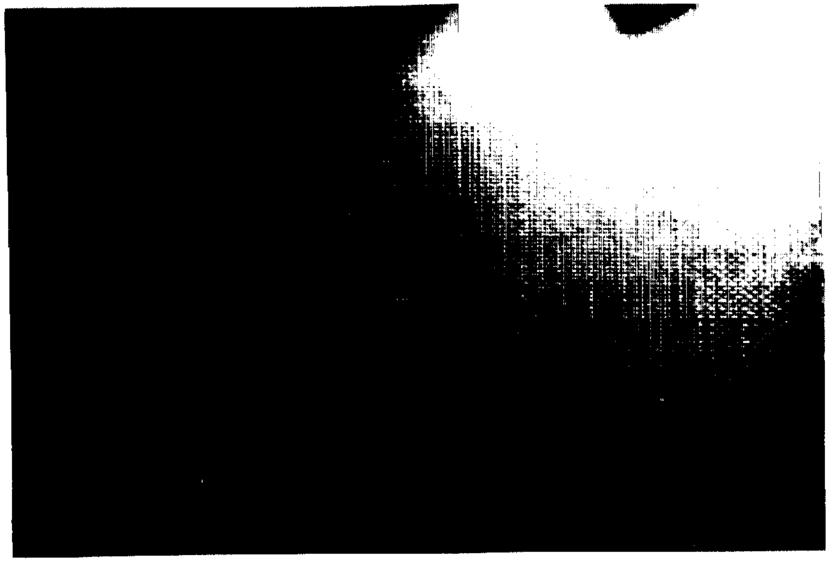
SPECTRA WITH EPOXY   IMPACT ENERGY 6 J



INSTRUMENTED OUTPUT



CROSS SECTION



FRONT

BACK

SPECTRA WITH EPOXY IMPACT ENERGY 8.5 J

REFERENCES

1. Lance, D.G., and Nettles, A.T.: "Low Velocity Instrumented Impact Testing of Four New Damage Tolerant Carbon/Epoxy Composite Systems." NASA TP 3029, July 1990.

2. Jang, B.Z., Chen, L.C., Wang, C.Z., Lin, H.T., and Zee, R.H.: "Impact Resistance and Energy Absorption Mechanisms in Hybrid Composites." Composites Science and Technology, vol. 34, 1989, pp. 305–335.

3. Busgen, A.W., Effing, M., and Scholle, M.: "Improved Damage Tolerance of Carbon Fiber Composites by Hybridization and Polyethylene Fiber, Dyneema SK 60." Proceedings of the American Society for Composites Fourth Technical Conference, Blacksburg, Virginia, October 3–5, 1989, pp. 418–424.

4. Miller, L.M.: "Characterization of Extended Chain Polyethylene/S-2 Glass, Interply Hybrid, Fabric Composites." M.S. thesis, Georgia Institute of Technology, July 1988.

5. Dorey, G., Sidey, G.R., and Hutchings, J.: "Impact Properties of Carbon Fiber/Kevlar 49 Fiber Hybrid Composites." Composites, vol. 9, 1978, pp. 25–32.

6. Winkel, J.D., and Adams, D.F.: "Instrumented Drop Weight Impact Testing of Cross-Ply and Fabric Composites." Composites, vol. 16, October 1985, pp. 268–278.

7. Sjoblom, P.O., Harntess, J.T., and Cordell, T.M.: "On Low-Velocity Impact Testing of Composite Materials." Journal of Composite Materials, vol. 22, January 1988, pp. 30–52.

8. Starnes, J.H., Jr., Rhodes, M.D., and Williams, J.G.: "Effect of Impact Damage and Holes on the Compressive Strength of a Graphite/Epoxy Laminate." Nondestructive Evaluation and Flaw Criticality for Composite Materials, ASTM STP 696, R.B. Pipes, Editor, American Society for Testing and Materials, 1979, pp. 145–171.

9. Sjoblom, P., and Hwang, B.: "Compression-After-Impact: The $5,000 Data Point!" 34th International SAMPE Symposium and Exhibition, vol. 24, Reno, NV, May 8–11, 1989, pp. 1411–1421.

10. Demuts, E., Whitehead, R.S., and Deo, R.B.: "Assessment of Damage Tolerance in Composites." Composites Structures, vol. 4, 1985, pp. 45–58.

11. Wyrick, D.A., and Adams, D.F.: "Residual Strength of a Carbon/Epoxy Composite Material Subjected to Repeated Impact." Journal of Composite Materials, vol. 22, August 1988, pp. 749–765.

12. Cantwell, W.J., and Morton, J.: "Detection of Impact Damage in CFR Laminates." Composite Structures, vol. 3, 1985, pp. 241–257.

13. Sun, C.T., and Norman, T.L.: "Design of Laminated Composite With Controlled-Damage Concept." Proceedings of the American Society for Composites Third Technical Conference, Seattle, WA, September 25–29, 1988, pp. 485–494.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
October 1991

3. REPORT TYPE AND DATES COVERED
Technical Paper

4. TITLE AND SUBTITLE
An Examination of the Damage Tolerance Enhancement of Carbon/Epoxy Using an Outer Lamina of Spectra®

5. FUNDING NUMBERS

6. AUTHOR(S)
D.G. Lance and A.T. Nettles

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M-671

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TP-3160

11. SUPPLEMENTARY NOTES
Prepared by Materials and Processes Laboratory, Science and Engineering Directorate.
"MSFC Center Director's Discretionary Fund Final Report," Project No. 90-17

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified — Unlimited
Subject Category: 24

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Low-velocity instrumented impact testing was utilized to examine the effects of an outer lamina of ultra-high molecular-weight polyethylene (Spectra) on the damage tolerance of carbon/epoxy composites. Four types of 16-ply quasi-isotropic panels, $(0, +45, 90, -45)_{s2}$, were tested. Some panels contained no Spectra, while others had a lamina of Spectra bonded to the top (impacted side), bottom, or both surfaces of the composite plates. The specimens were impacted with energies up to 8.5 J. Force-time plots and maximum force versus impact energy graphs were generated for comparison purposes. Specimens were also subjected to cross-sectional analysis and compression-after-impact tests. The results show that while the Spectra improved the maximum load that the panels could withstand before fiber breakage, the Spectra seemingly reduced the residual strength of the composites.

14. SUBJECT TERMS
Composite Materials, Compression-After-Impact Testing, Damage Tolerance, Instrumented Impact Testing

15. NUMBER OF PAGES
32

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT
Unlimited

NASA-Langley, 1991