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CROSS-SECTIONAL EXAMINATION OF THE DAMAGE ZONE IN IMPACTED SPECIMENS OF CARBON/EPOXY AND CARBON/PEEK COMPOSITES

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Science and Engineering Directorate

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16. Abstract

Drop weight impact testing was utilized to inflict damage on eight-ply bidirectional and unidirectional samples of carbon/epoxy and carbon/PEEK (polyetheretherketone) test specimens with impact energies ranging from 0.80 J to 1.76 J. The impacting tup was of a smaller diameter (4.2-mm) than those used in most previous studies, and the specimens were placed over a hole 10.3 mm in diameter to obtain a puncture type of impact. The specimens were cut with a diamond wheel wafering saw through the impacted area perpendicular to the outer fibers. Photographs at 12 x magnification were taken of these cross-sections and examined. The results on the bidirectional samples show little damage until 1.13 J, at which point delaminations were seen in the epoxy specimens. The PEEK specimens showed less delamination than the epoxy specimens for a given impact energy level. The unidirectional specimens displayed more damage than the bidirectional samples for a given impact energy, with the PEEK specimens showing much less damage than the epoxy material.

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CROSS-SECTIONAL EXAMINATION OF THE DAMAGE ZONE IN IMPACTED SPECIMENS OF CARBON/EPOXY AND CARBON/PEEK COMPOSITES

I. INTRODUCTION

In order for composite materials to become more widely accepted as a structural material, a better understanding of the properties of the many types of fiber/resin systems must be obtained. One of the least attractive properties of carbon fiber composites is their impact resistance. However, the development of thermoplastic resins has resulted in tougher composites that show promise both as a more impact-resistant composite and as a good candidate for rapidly produced parts with smaller production times than those of thermoset resins.

Instrumented impact testing has been of great use in assessing the damage process of an impacted composite specimen. Force-time and absorbed energy-time curves can be generated for the impact event. Previous studies have shown that a critical impact energy level exists at which point the specimen will exhibit a rapid loss of strength with increasing impact energy [1–5]. To obtain a more detailed examination of the type of damage occurring at various impact energy levels, especially those within the critical impact energy zone, cross-sectioning the specimens through the damaged area and observing the inflicted damage with microscopic magnification can prove to yield important information [2,6–8]. The first sign of damage in most of these studies has been matrix cracking, followed by delamination between plies, then fiber breakage. However, most of the studies utilized composites of 16 plies or more, with panels to be impacted supported by placing them over a hole many times greater than the tup size. This type of support fixture allows for greater flexing of the specimen as compared to one which is supported over a hole slightly larger than the impacting tup which would produce more of a puncture type of impact.

Composite panels utilizing carbon/epoxy or carbon/PEEK produce a lightweight, strong, stiff structure that can have many beneficial uses in spacecraft, aircraft, sporting goods, and many other products. Accidents during handling or use of these panels may cause damage that may or may not be visible. Tool drops, runway debris, and rough handling can produce a puncture type of impact damage that may have an adverse affect on the part. Therefore, a better understanding of the damage process can aid the designer and utilizer in determining how to design a part or whether a part is still useable after an impact event.

The question of which type of polymeric resin is best suited for the part to be designed can be based on many factors including impact resistance. It has been concluded in most impact studies which compared aromatic polymers with epoxy-based resins that the aromatic polymer is tougher [4,9,11]. However, the purpose of this study is to determine the damage process of epoxy and PEEK resin-based composites which sustain a puncture type of impact.

II. DESCRIPTION

A. Materials and Test Methods

1. Material. The two materials tested were AS4/3501, which is a standard carbon/epoxy system, and AS4/APC-2, which is a carbon/PEEK system. Both of these materials had fiber weight fractions of 69 percent and were laminated in eight-ply bidirectional and unidirectional configurations. Square panels 30.5×30.5 cm in size were produced from the materials and eight strips of dimension 2.54×30.5 cm were cut from each panel. The thickness of both the epoxy and PEEK specimens was 1.02 mm.

2. Impact Testing. Specimens were impacted using a TMI 43-21 drop weight instrumented impact tester. Data were obtained with a Dynatup 730 data acquisition system. The impacting head had a mass of 1.5 kg with a hemispherically ended tup of diameter 4.2 mm. The specimens were clamped in place between two aluminum plates as shown in Figure 1. A hole of 10.3-mm diameter was present in the center of each plate to allow the tup to pass through. The bottom hole was chamfered to 12.7 mm in diameter to prevent the hole edges from cutting a circular groove into the specimen. A bubble level capable of measuring levelness in 360° was placed on the top plate to assure an even clamp.

Impact energy levels were varied by changing the drop height of the impacting head. This impacting head was released manually, thus producing slight variations in measured impact energy at a given drop height. Drop heights of 7.6, 10.2, 11.4, 12.7, and 15.2 cm were used for each of the two bidirectional materials tested. Drop heights of 7.6, 10.2, and 12.7 cm were used for the unidirectional samples.

3. Specimen Cross-Sectioning. All of the impacted specimens were cross-sectionally cut through the point of impact in a direction perpendicular to the outer fibers using a small diamond wheel cutter. These cross-sections were then observed and photographed at 12 x magnification.

B. Test Results and Discussion

1. Impact Testing of Bidirectional Samples. The force-time plots of the bidirectional specimens tested are given in Figure 2. For both the epoxy and PEEK matrices, a small drop in the force-time plot can be seen during the early stages of the impact event. This "incipient damage" can be seen at drop heights which produce no visible damage and is fairly constant in value for any given material system. This result has been seen in other impact studies such as the one conducted by Aleska [12]. The "damage" may in fact be a drop in force due to a shock wave rebound effect. A more intense study is necessary to determine what is the source of this small initial drop in force.

At drop heights which produced easily noticeable visual damage, a large drop in the force-time curve is observed at the peak force indicating fiber breakage.

The smooth curves superimposed on the force curves are absorbed energy curves. In a previous study on various carbon/epoxy systems, it was observed that between 73 and 85 percent of the initial impact energy was lost during impact regardless of the value of the initial impact energy [5]. This held true up until the point of fiber breakage where a much larger percentage of energy was lost (usually close to 100 percent). It is suspected that most of the energy lost in the stages before fiber breakage is due to vibrational losses in the impacting head. It has been shown [13] that large vibrational waves are present in a rod impacted on its end. This form of energy loss in instrumented impact testing has also been noted in another study [7]. Thus it is not recommended to assume all or even most of the absorbed energy data represents energy absorbed as damage to the impacted specimen.

2. Visual Surface Examination of Bidirectional Samples. A visual examination of the impacted specimens before cross-sectioning showed a very small indentation for the epoxy system at impact energies of 0.80 and 1.13 J. Larger indentations were seen at 1.26, 1.36, and 1.76 J impact energies with some tension (bottom) side fiber breakage and matrix splitting. The PEEK specimens showed larger indentations on the impacted surface for the 0.80, 1.11, and 1.26 J energy levels. At the 1.30 and 1.75 J energy levels, the PEEK samples exhibited some matrix cracking on the tension side, but not to the extent of the epoxy samples.

3. Cross-Sectional Examination of Bidirectional Samples. Figure 2 also shows the cross-sectional photographs at 12 x magnification for the bidirectional specimens. No damage can be seen for the 0.80 J impact, but the 1.13 J impact produced delaminations between the third and fourth and the fifth and sixth layers. It should be noted that this damage does not produce significant drops in the force-time curve, but rather small undulations near the peak force as seen in Figure 2c. An impact energy of 1.26 J produced fiber breakage from the fourth layer on down to the bottom layer and delamination between the third and fourth and the sixth and seventh layers. At 1.36 J the specimen shows fiber breakage with delamination between the seventh and eighth layers, and at 1.76 J the specimen shows major fiber breakage and delamination through the specimen. At this impact energy level, the tup totally penetrated the specimen. The force-time traces for the 1.26, 1.32, and 1.76 J energy levels exhibit large drops in force at the peak of the force-time curve due to the fiber breakage which was much more extensive on the tension side of the specimen.

The cross-sectional photographs of the PEEK specimens are presented in Figure 2 paired with the epoxy specimens by impact drop height. At 0.80 J the specimen displayed a slight depression on its impacted side. What appears to be upper fiber breakage is in actuality a splinter that was peeled from the sliced specimen between the cross-sectioning and photographing phases of this study. No delamination has occurred at this point. The PEEK specimen impacted at 1.11 J displays a slight depression on its impacted side with no delamination present. An impact energy of 1.26 J produced a large indentation, but still no delamination or fiber breakage. A heavy extent of damage is present at an impact energy level of 1.30 J. This damage includes fiber breakage and delaminations and looks much like the epoxy specimen impacted at 1.30 J. The 1.75 J impact energy level produced slightly more delamination and fiber breakage than the 1.30 J impact energy level, but did not display the extent of damage found in the epoxy specimen impacted at 1.76 J. Furthermore, complete penetration did not occur at this impact energy as it did in the epoxy specimens.

4. Impact testing of Unidirectional Samples. The force-time plots and corresponding cross-sectional photographs of the unidirectional samples are given in Figure 3. The impact damage sustained by the unidirectional samples is much more dependent on matrix shear toughness than the bidirectional samples since there are no cross fibers to help prevent matrix shear failure during a puncture type of impact as shown in Figure 4.

A comparison of the PEEK and epoxy samples at the first impact energy (drop height of 7.6 cm) clearly shows the superior impact resistance of the PEEK matrix. Only a small indentation in the specimen is seen for the PEEK sample, whereas much matrix cracking and shear failure are exhibited by the epoxy sample. The force-time plots at this drop height reveal the dramatic difference beyween the two materials since the PEEK sample withstood a force of about 0.75 kN, and the epoxy specimen could only sustain a force of about 0.60 kN at which point a large drop in force occurred. Unlike the bidirectional samples, this large drop in force does not necessarily correspond to fiber breakage, but to through-the-thickness matrix damage. As can be seen from the absorbed energy curves, no rebound occurred at the 7.6-cm drop height for the eopxy, but did occur for the PEEK specimen. In fact, the absorbed energy curve for the epoxy continues to display energy being absorbed after penetration. This is due to the impacting cross-head slamming into the rubber stoppers used to keep the instrumented part of the tup from colliding with the specimen. At the 10.2-cm drop height, the PEEK specimens displayed no matrix cracking with only a large plastic deformation occurring. The epoxy specimen suffered severe damage at this drop height as can be seen from the photograph in Figure 3c. At the 12.7-cm drop height, the PEEK sample shows through-the-thickness damage with total tup penetration, and the epoxy sample shows that a hole was punched through the specimen.

III. CONCLUSIONS

The PEEK matrix system demonstrated a higher impact tolerance than the epoxy matrix system when damaged with a puncture type of impact, which is not surprising since thermoplastic matrices have shown superior damage tolerance in other studies [4,9,11]. The PEEK samples tested in this study did show more of an indentation at the impact zone than the epoxy samples, but the cross-sectional examination showed no delamination or fiber breakage in the bidirectional samples until 1.30 J of impact energy was exerted on the specimen. These large indentations are due to the PEEK material being able to deform more plastically than the brittle epoxy resin.

The unidirectional specimens tested emphasized the superior impact resistance of the PEEK resin over the epoxy resin. Much less matrix cracking was exhibited by the PEEK specimens for all of the energy levels used on the unidirectional samples.

While the bidirectional samples did not show as large a variation in damage, they did demonstrate how the epoxy samples delaminated much more easily than the PEEK samples.

The next phase of this study is to determine residual tensile and compressive strengths for the materials used in this study. It is expected that residual tensile strength will not be greatly reduced in either material until fiber breakage occurs, but residual compressive strength can be greatly affected by matrix cracking and interply delaminations. Also, it is of interest to see if the large plastic deformations of the PEEK material that result in visual indentations will cause localized buckling and failure of the specimens tested in compression.

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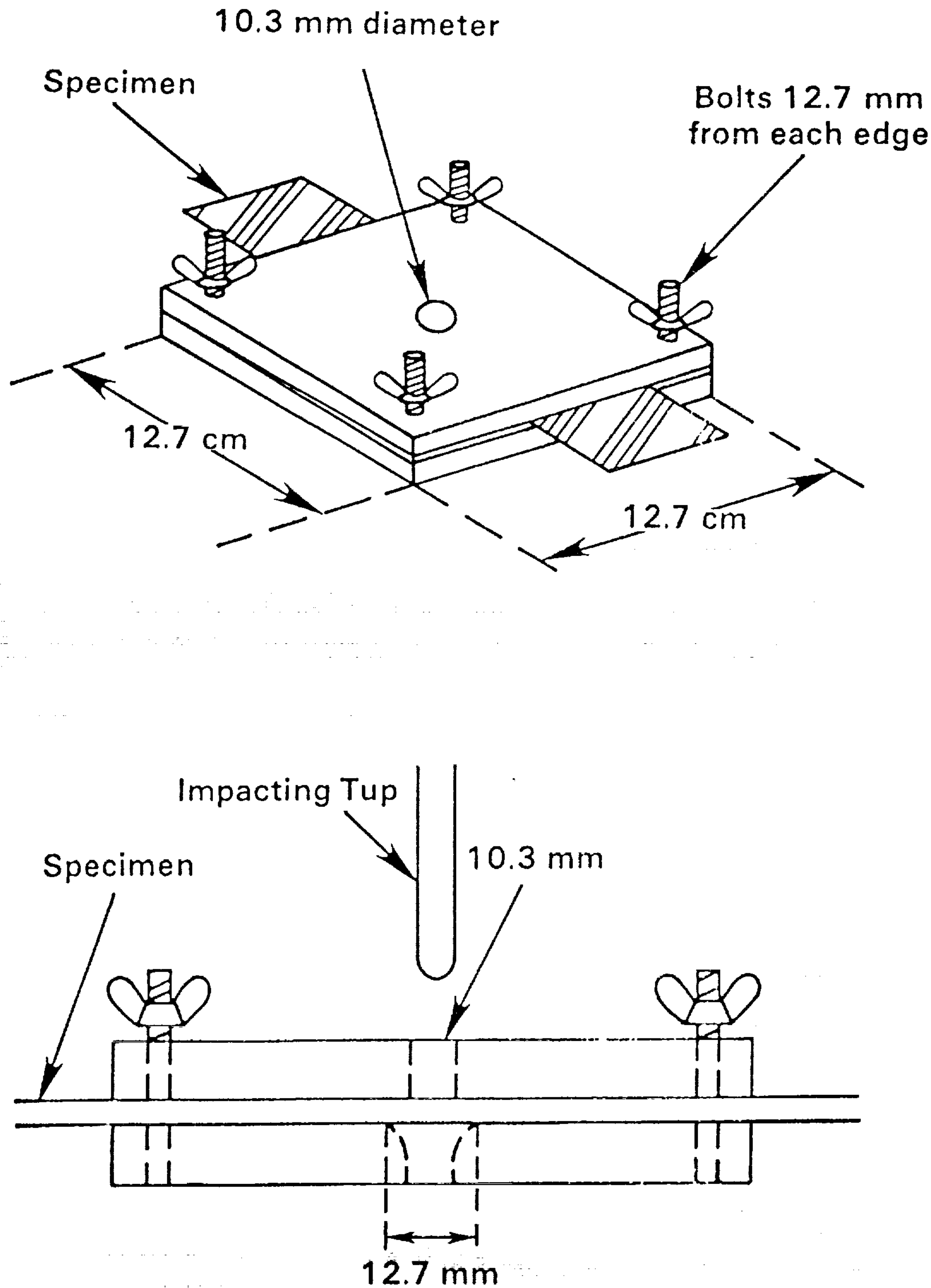


Figure 1. Support fixture for specimens to be impacted.

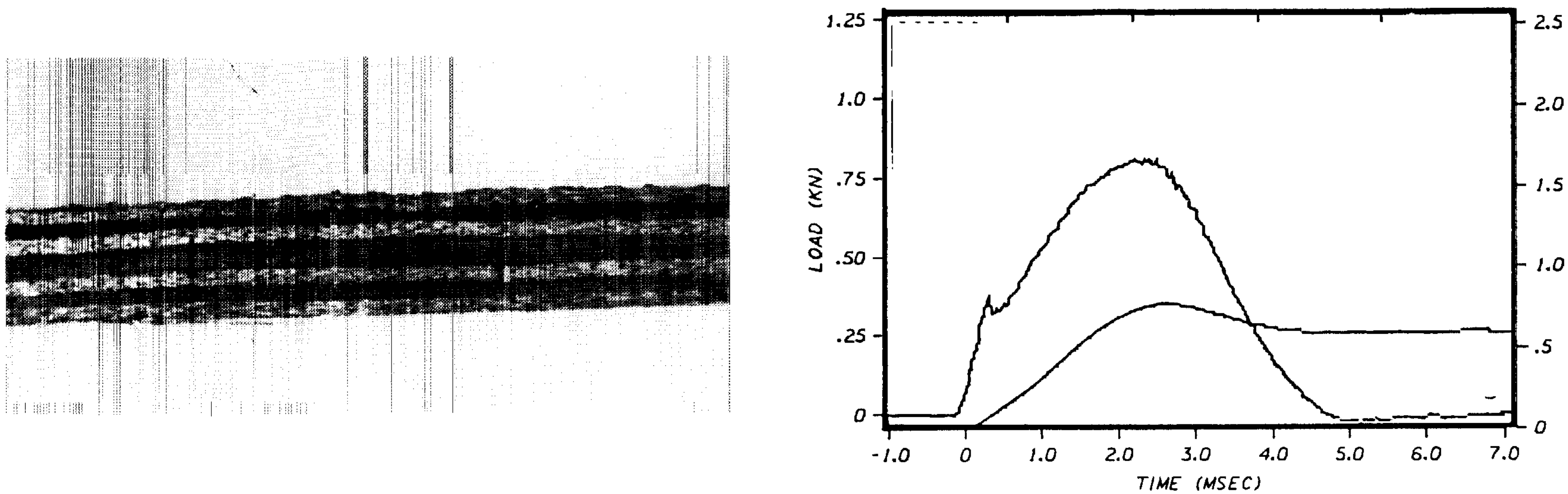


Figure 2a. Bidirectional epoxy specimen impacted from 7.6-cm drop height.
Impact energy of 0.80 J.

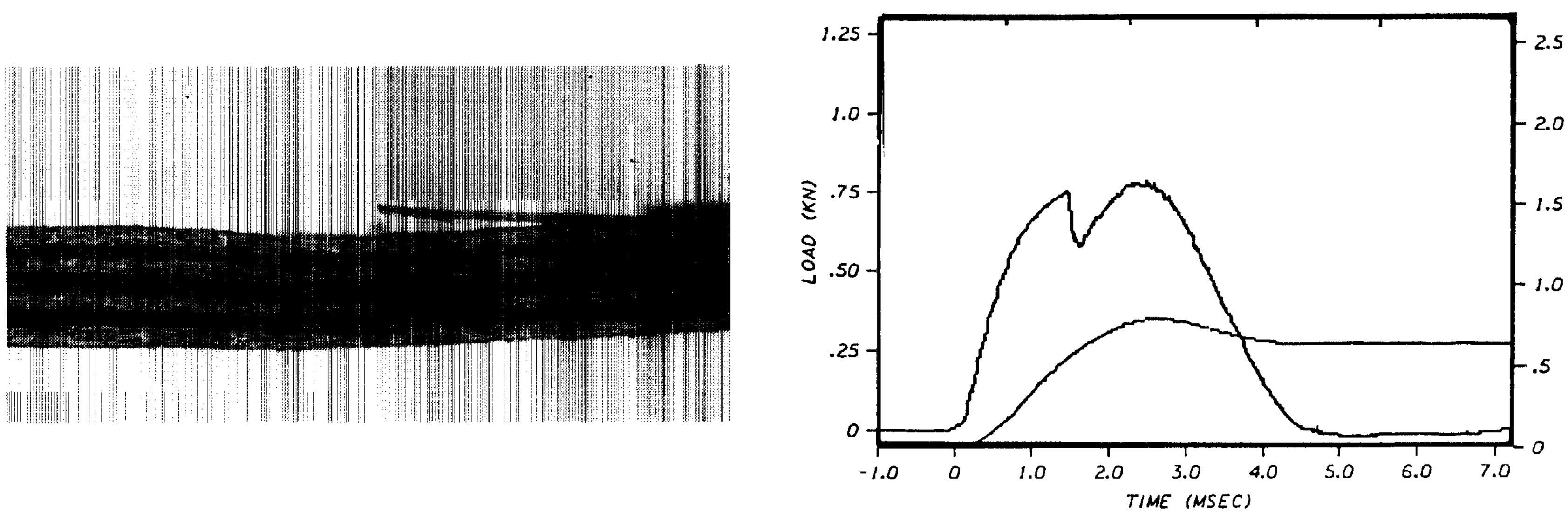


Figure 2b. Bidirectional PEEK specimen impacted from 7.6-cm drop height.
Impact energy of 0.79 J.

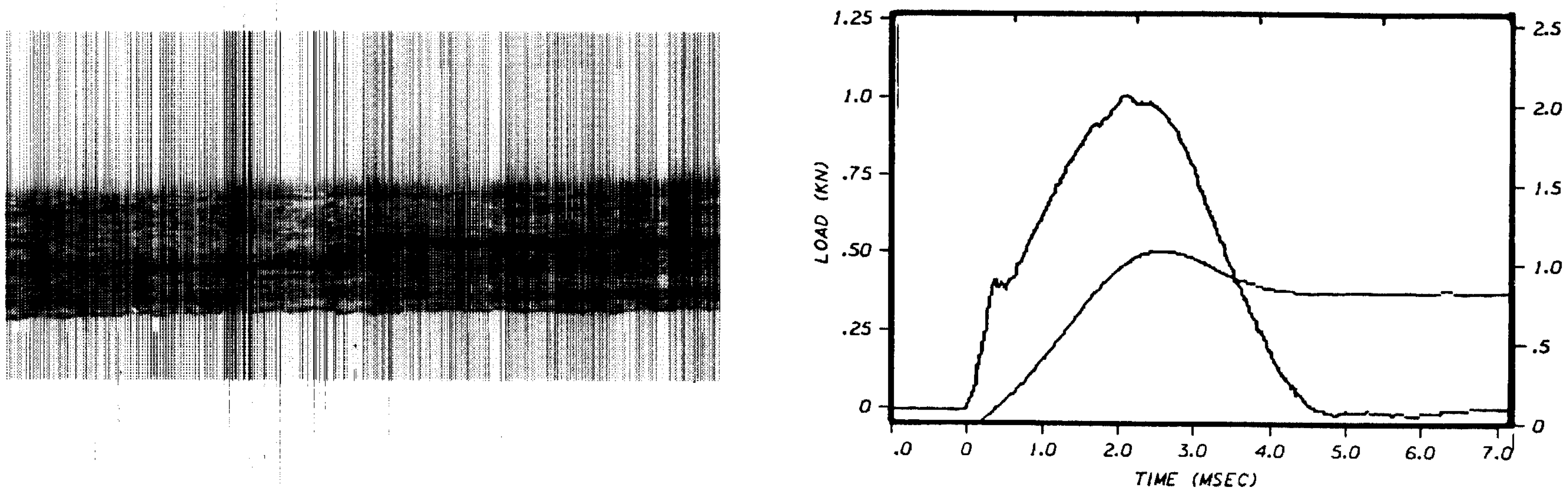


Figure 2c. Bidirectional epoxy specimen impacted from 10.2-cm drop height. Impact energy of 1.13 J.

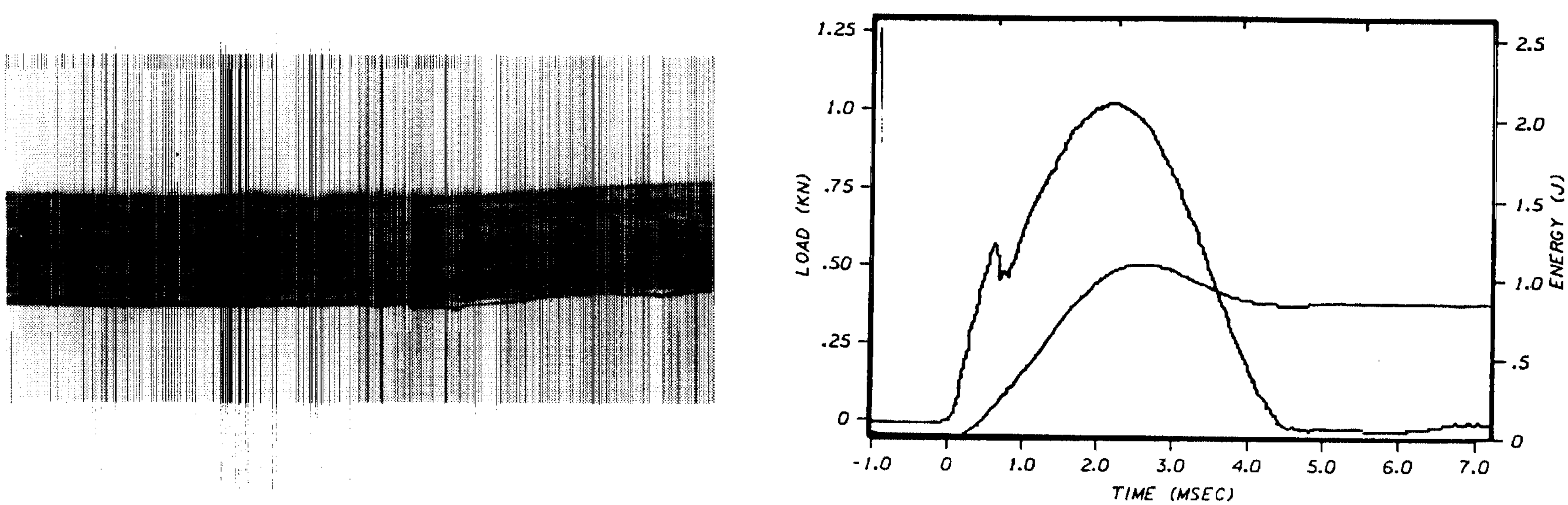


Figure 2d. Bidirectional PEEK specimen impacted from 10.2-cm drop height. Impact energy of 0.11 J.

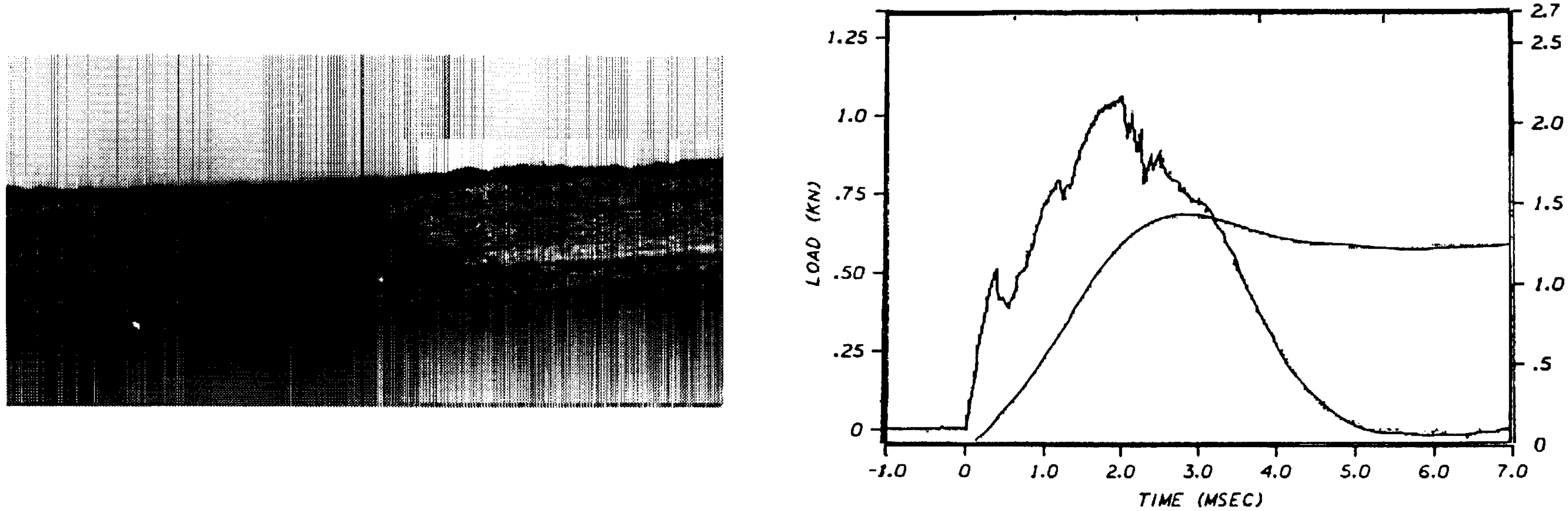


Figure 2e. Bidirectional epoxy specimen impacted from 11.4-cm drop height.
Impact energy of 1.41 J.

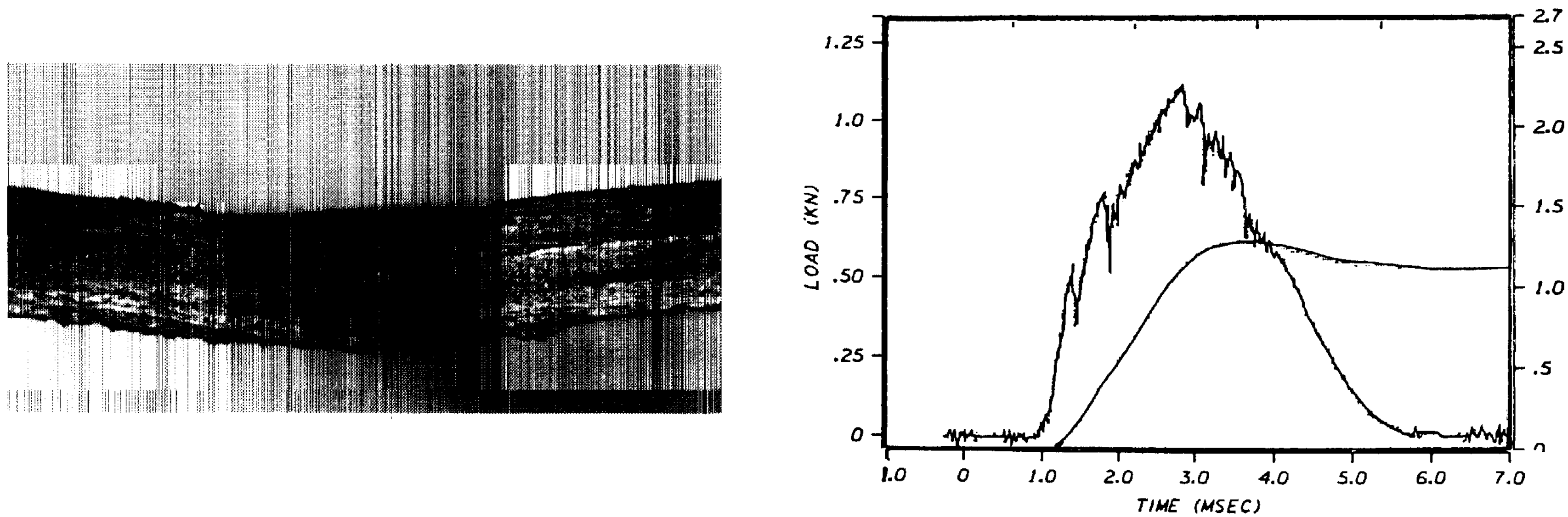


Figure 2f. Bidirectional PEEK specimen impacted from 11.4-cm drop height.
Impact energy of 1.26 J.

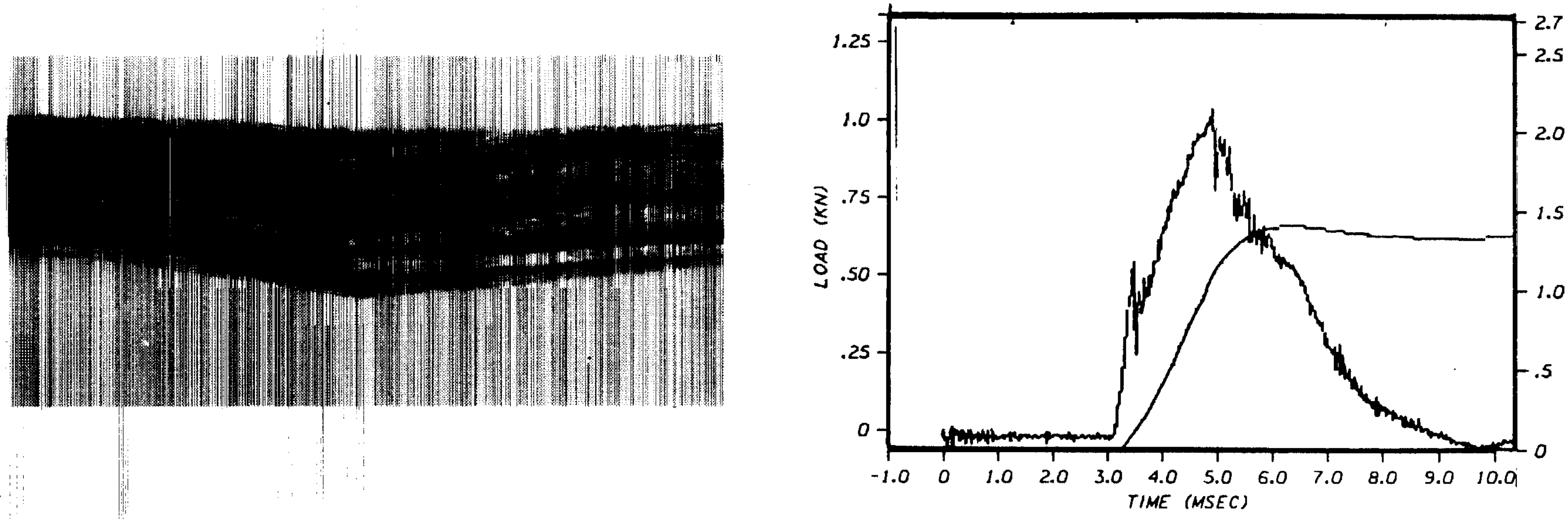


Figure 2g. Bidirectional epoxy specimen impacted from 12.7-cm drop height. Impact energy of 1.30 J.

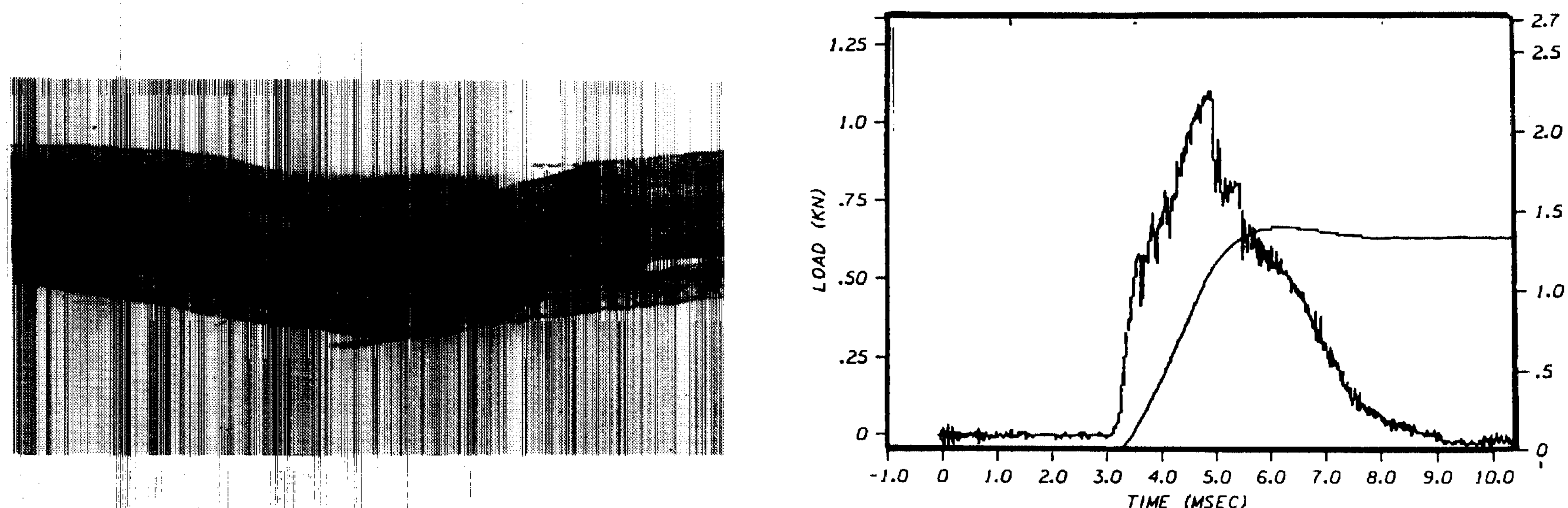
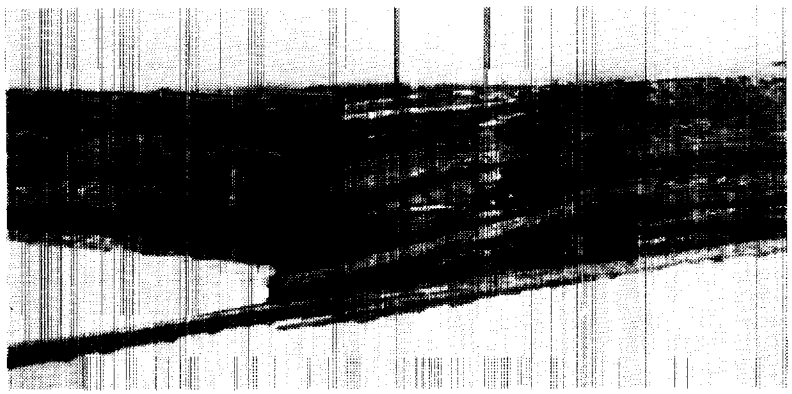


Figure 2h. Bidirectional PEEK specimen impacted from 12.7-cm drop height. Impact energy of 1.30 J.



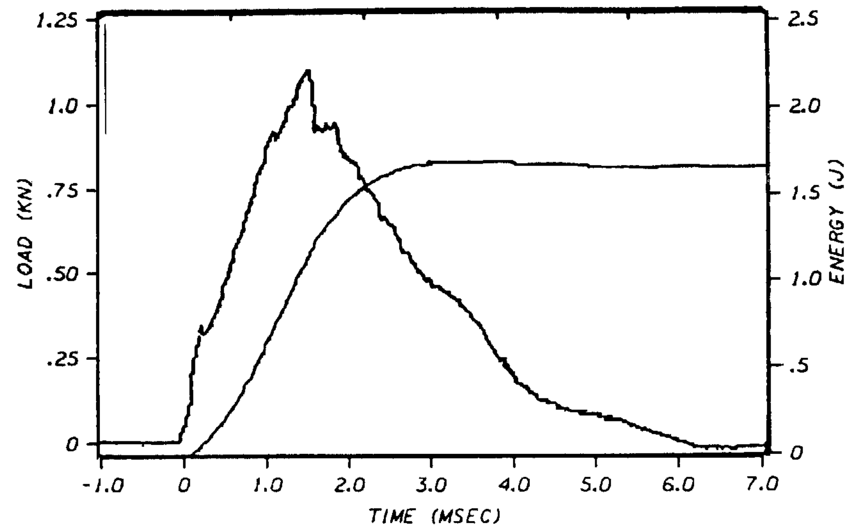
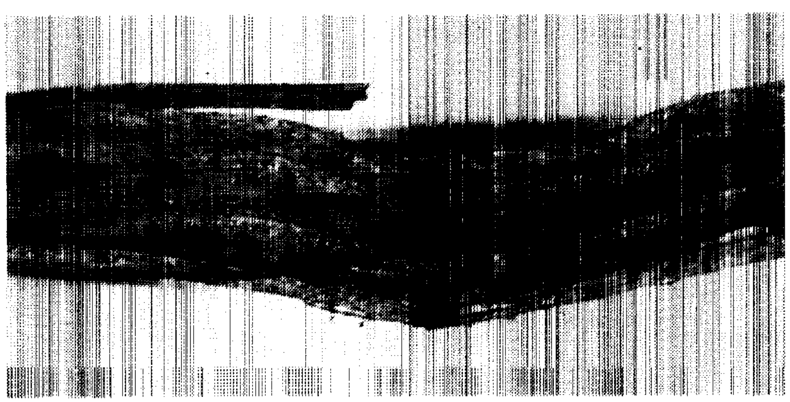


Figure 2i. Bidirectional epoxy specimen impacted from 15.2-cm drop height. Impact energy of 1.76 J.



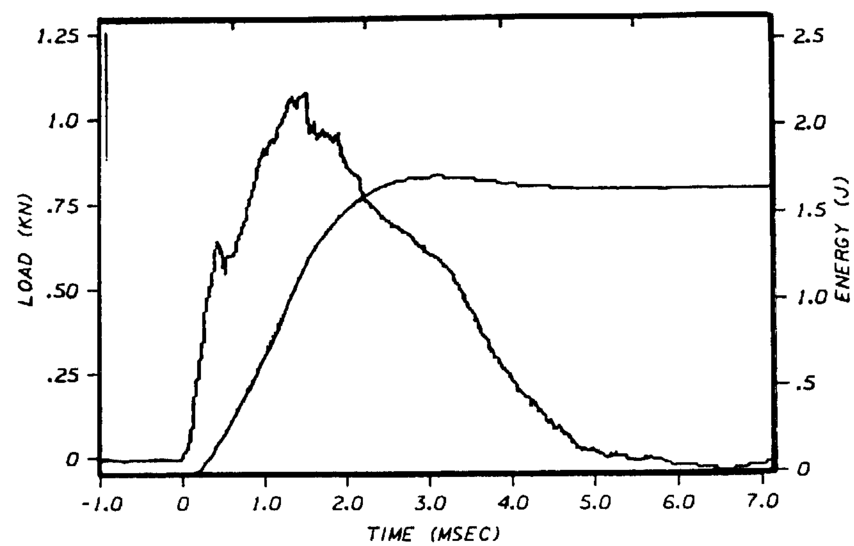


Figure 2j. Bidirectional PEEK specimen impacted from 15.2-cm drop height. Impact energy of 1.75 J.

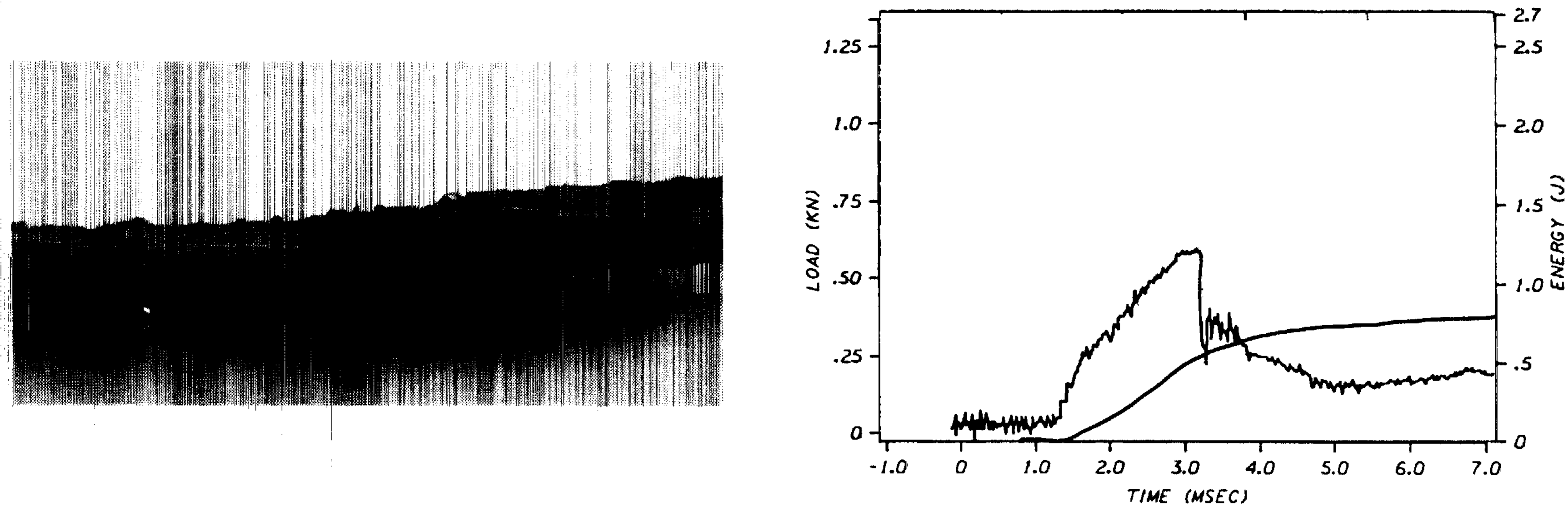


Figure 3a. Unidirectional epoxy specimen impacted from 7.6-cm drop height. Impact energy of 0.75 J.

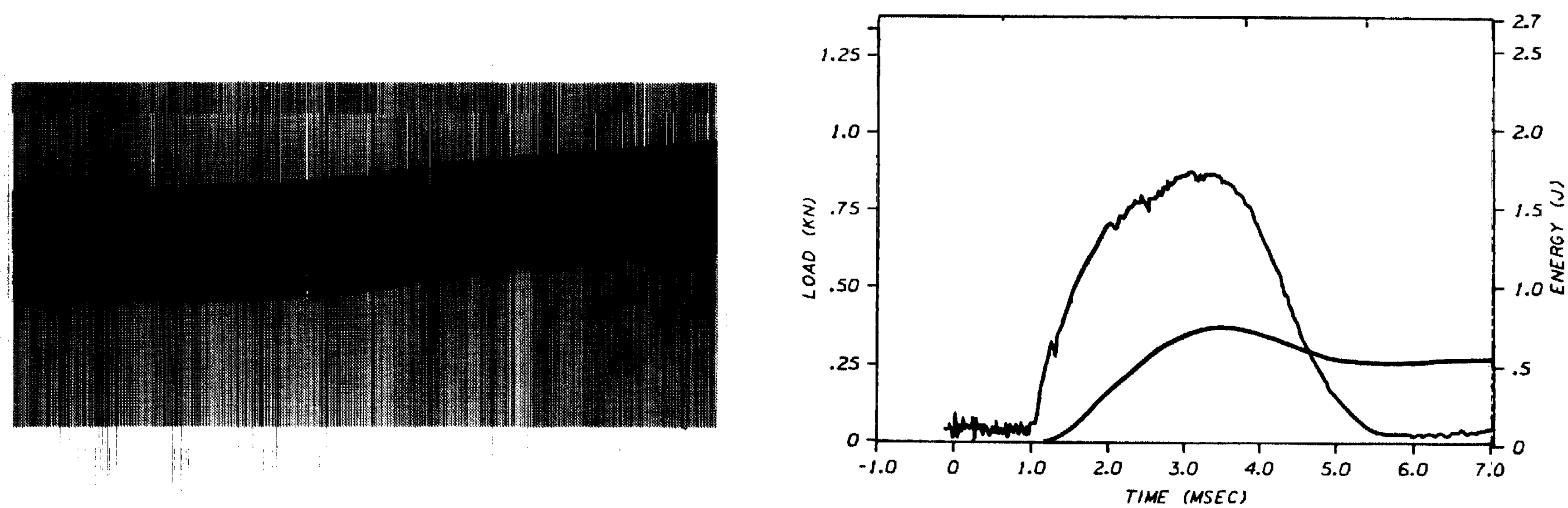


Figure 3b. Unidirectional PEEK specimen impacted from 7.6-cm drop height. Impact energy of 0.75 J.

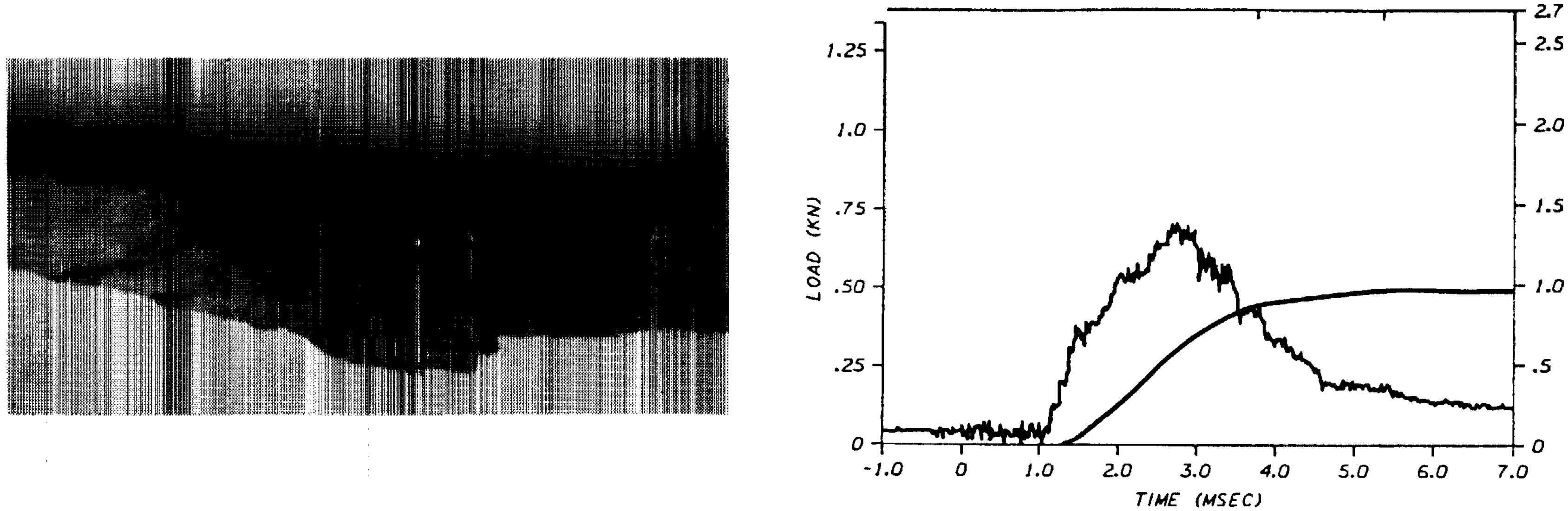


Figure 3c. Unidirectional epoxy specimen impacted from 10.2-cm drop height. Impact energy of 0.98 J.

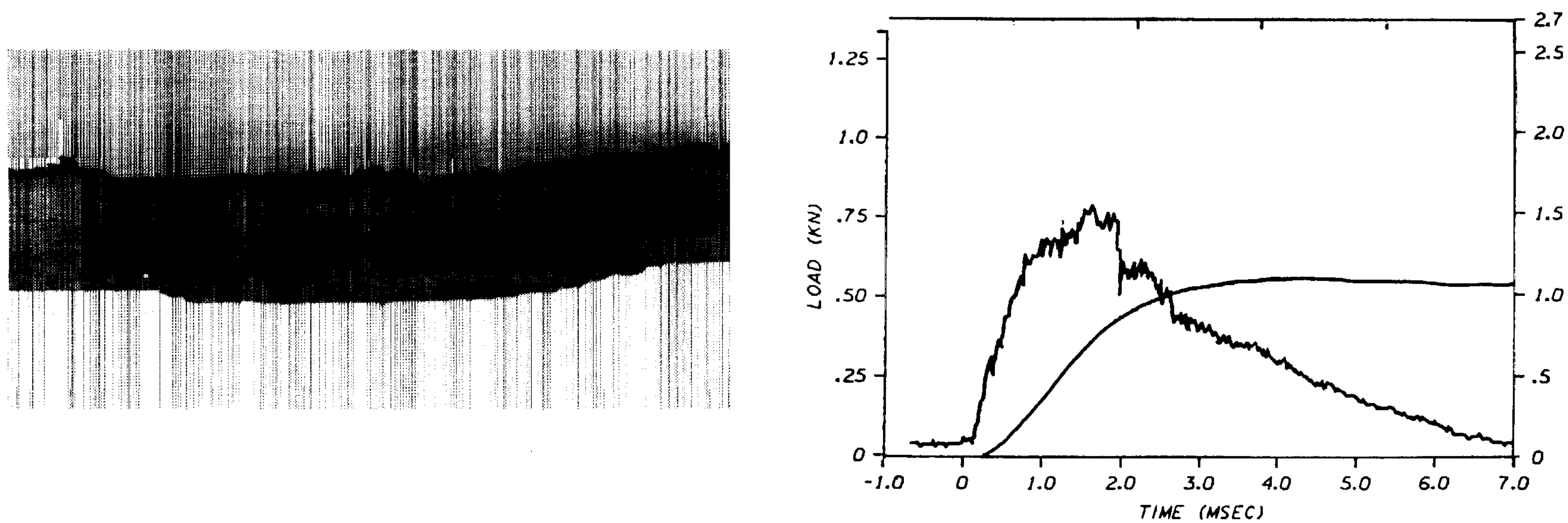


Figure 3d. Unidirectional PEEK specimen impacted from 10.2-cm drop height. Impact energy of 0.98 J.

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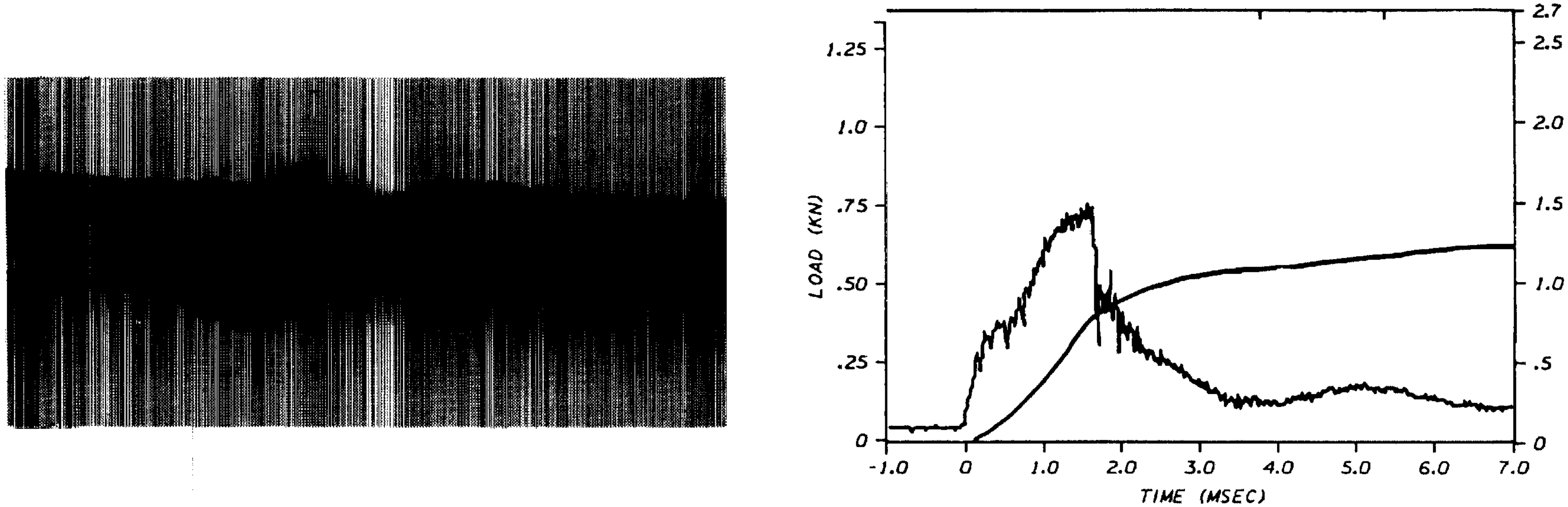

Figure 3e. Unidirectional epoxy specimen impacted from 12.7-cm drop height. Impact energy of 1.21 J.

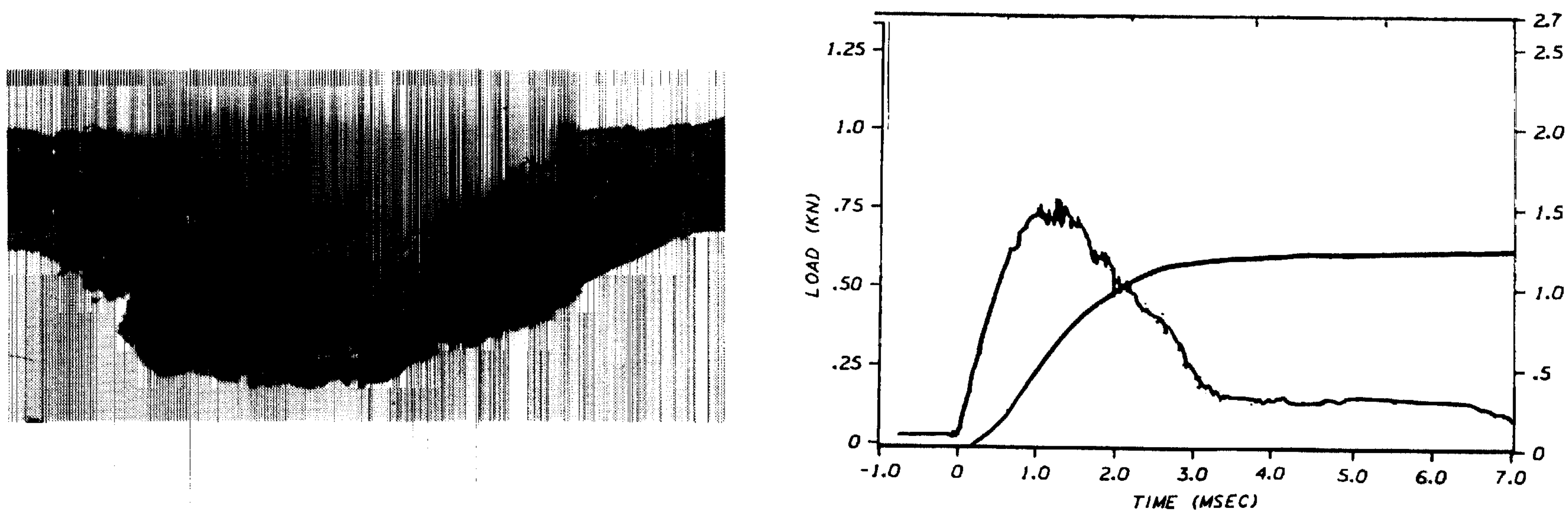

Figure 3f. Unidirectional PEEK specimen impacted from 12.7-cm drop height. Impact energy of 1.21 J.

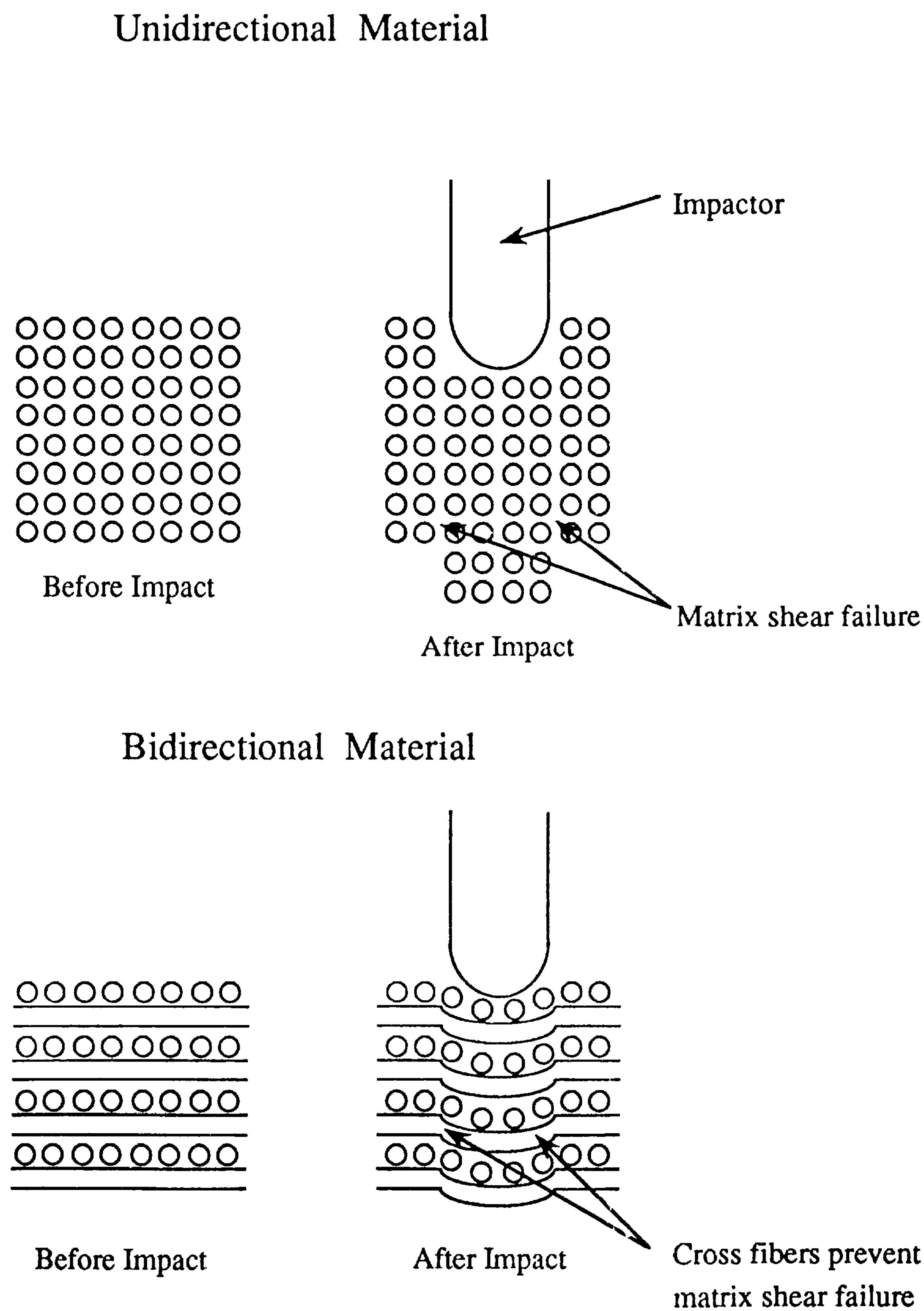

Figure 4. Damage mechanisms for unidirectional and bidirectional samples.

APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

PAUL H. SCHUERER
Director, Materials and Processes Laboratory

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