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# Ordnance Impacts on Jet Engine Fan Blades

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# ORDNANCE IMPACTS ON JET ENGINE FAN BLADES

*UNIVERSITY OF DAYTON RESEARCH INSTITUTE*
*300 COLLEGE PARK AVENUE*
*DAYTON, OHIO 45469*

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James S Wilbeck

J. S. Wilbeck, Capt. USAF
Project Engineer

FOR THE COMMANDER

V J Russo

Dr. V. Russo, Chief
Metals Behavior Branch
Metals & Ceramics Division
Air Force Materials Laboratory

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Ballistic perforation, ballistic limits, momentum transfer, bullet impact, foreign object damage, bullet perforation.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the experimental section of a program to investigate the damage that a .50 cal ogive inflicts on typical jet engine fan blade materials. Three materials, titanium, graphite epoxy composite and boron aluminum composite, were perforated by .50 caliber ogives at 488 m/s. Two impact obliquities were investigated, 90° and 60° to trajectory. The momentum transfer during the impact was measured by use of a ballistic pendulum on which the targets were mounted. The momentum transfer was greatest for titanium, considerably lower for boron aluminum and even lower for graphite epoxy.

1a

20. ABSTRACT (continued)

The results agree favorably with the calculated values at 90° but differ at 60°.

# FOREWORD

This report describes research conducted by the University of Dayton at the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio under contract F33615-75-C-5052.

The work was conducted during the period January 1975 to July 1975. The contract monitor was Dr. Alan Hopkins of the Air Force Materials Laboratory.

This report was submitted by the authors in February 1976 for publication as a Materials Laboratory Technical Report.

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# SECTION I

## INTRODUCTION AND BACKGROUND

Impact of jet engine fan blades by ordnance projectiles and birds presents a severe threat to aircraft survivability. Impacts of bird carcasses, rocks, and munitions can result in large tip deflection, perforation and possible breakage of a blade. Tip deflection and blade debris resulting from impact can involve adjacent blades, multiplying the damage. In addition, modern gas turbine engines utilize blades made from lightweight composite blade materials which may be more vulnerable to certain types of impact.

This program is concerned with two basic types of impact; hard body and soft body. Hard objects tend to retain their size and shape during the impact event leading to intense localized damage at the impact site with relatively slight effects at large distances. Impact by hard bodies, such as ordnance projectiles, result in perforation of the blade knocking out plugs of blade material and creating other blade debris.

Soft bodies, on the other hand, deform massively upon impact and produce less localized damage but significantly larger effects at long distances, largely due to the greater total impulse transferred to the target during impact. Impact by soft bodies produce large tip deflection of the blade and often results in blade breakage at or near the root of the blade.

The study was divided into two phases because of the fundamental differences between the phenomena of impacts by hard and soft bodies. Phase 1 was a study of hard body impacts and Phase 2 will be a study of soft body impacts.

Both phases involve an analytic study and an experimental verification. The analytic study is being conducted by California Research and Technology Inc. (CRT) Woodland, California, under subcontract to UDRI.

The analysis consists of finite difference calculations employing a 2-D finite difference Lagrangian code, WAVE-L, to determine the blade material response to various impact conditions.

The experimental verification conducted by UDRI consists of mounting samples of blade material aboard a ballistic pendulum to determine the momentum transfer to the target material.

This report is concerned with the experimental part of Phase 1 only. The analytic effort will be reported separately by CRT.

## SECTION II

## HARD BODY DAMAGE

### 2.1 IMPACT CONDITIONS STUDIED

The purpose of the experimental phase is to duplicate a set of impact conditions used in the finite difference calculations to verify the calculated results. The conditions examined experimentally are outlined below.

| | |
|---|---|
| Impact velocity: | 488 m/s |
| Projectile: | .50 caliber hardened steel ogive |
| Impact obliquity: | 90° and 60° to trajectory |
| Target material: | homogeneous 1/8" thick Ti-6-4<br>metal matrix 1/8" thick BAl<br>non-metal matrix 1/8" thick graphite/epoxy |

### 2.2 EXPERIMENTAL PROCEDURE

#### 2.2.1 Measurement of Momentum with a Ballistic Pendulum

The momentum transfer to the target material during impact is determined by mounting the material aboard a ballistic pendulum. The impact transfers kinetic energy into the pendulum system. This input of energy results in a displacement of the pendulum in the gravitational field which converts the kinetic energy into potential energy. The maximum potential energy which is equal to the total energy input to the system can be determined from the maximum height (vertical displacement) of the pendulum during the swing as shown in Figure 1. The momentum transfer therefore is given by:

$$\Delta P = m\sqrt{2gd}, \qquad (1)$$

where m is the mass of the pendulum structure after impact, d is the maximum vertical displacement and g is the gravitational acceleration.

The chord of the arc of the pendulum's swing, X, is more easily observed than the deflection d. X is related to d by

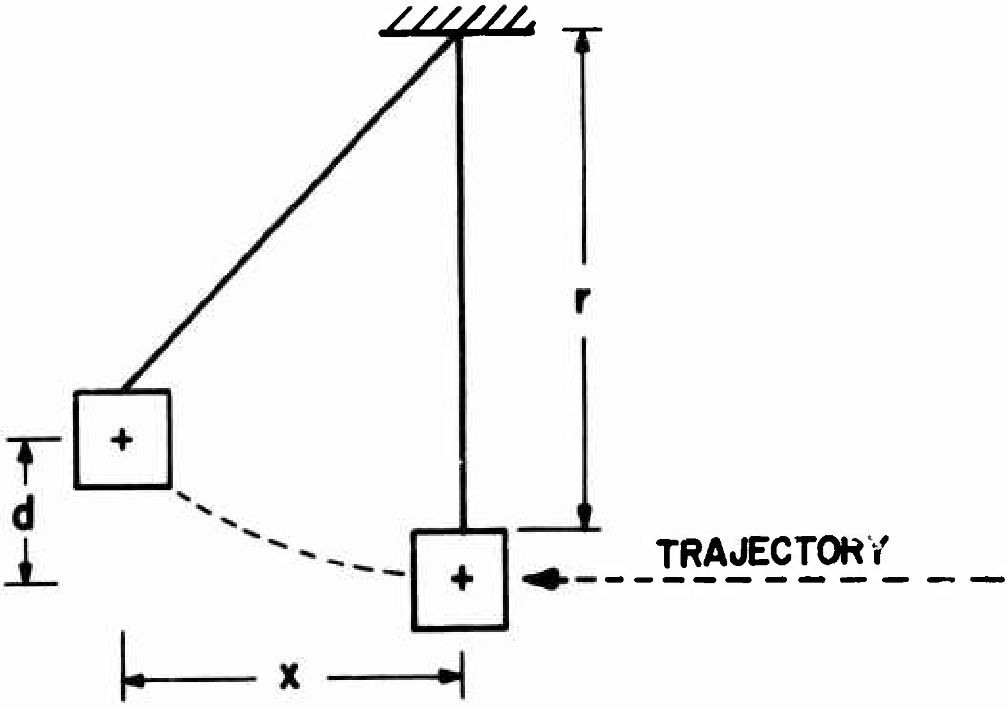


Figure 1. A Schematic of a Ballistic Pendulum

$$d = X^2/2r \ , \qquad (2)$$

from the Pythagorean theorem if $d^2$ is considered to be negligible (i.e., small displacements). The momentum transfer using the chord of the arc is therefore;

$$\Delta P = mX\sqrt{g/r}. \qquad (3)$$

The momentum transfer is also related to the period of the pendulum, $\tau$, (which can be easily measured experimentally) as

$$\tau = 2\pi\sqrt{r/g} \text{ and}$$
$$\Delta P = 2\pi \ mX/\tau \ . \qquad (4)$$

Accurate measurement of the momentum transfer to the pendulum is therefore facilitated by accurate determination of the period and mass of the pendulum and measurement of the chord of the arc created by the displacement.

### 2.2.2 Design of Pendulum

The ballistic pendulum used for the experimental verification was a classical five wire pendulum as shown in Figure 2. The five wire configuration eliminates all the rotational and all but two of the translational degrees of freedom of the pendulum. Motion is only permitted in the desired plane.

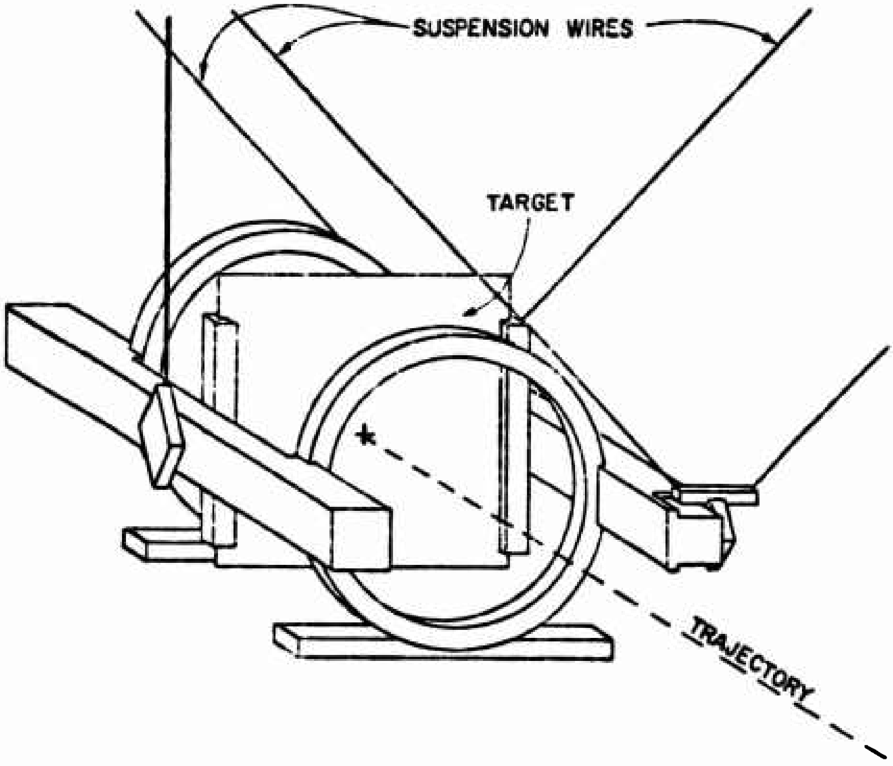


Figure 2. A Five Wire Ballistic Pendulum

The mass of the pendulum was adjusted to provide angles of displacement of less than 5° to preserve the accuracy of the momentum transfer measurement and small angle approximation. A maximum pendulum mass of approximately 20 kg was sufficient for this

### 2.2.3 Calibration of the Ballistic Pendulum

The pendulum was calibrated using measurements of period and a known momentum transfer. The period of the pendulum was calibrated by attaching a spring trip wire mounted in a position to make momentary contact with an appendage on the pendulum frame twice during each complete oscillation. The momentary trip wire contact closed an electric circuit providing start/stop signals for an electronic time interval counter. The period was measured for ten complete cycles. Several repetitions of this measurement indicated that the deviation was less than 0.0005 sec/cycle, and the accuracy of the period was within 1 ms.

The calibration of momentum transfer measurement was determined by conducting a totally inelastic collision of a projectile of known mass and velocity, with a thick aluminum target mounted in the pendulum. After making minor adjustments to the system and repeating this test several times, momentum transfer could be determined from the pendulum to within 1% of the actual input.

# SECTION III

## RANGE INSTRUMENTATION AND DATA COLLECTION

Figure 3 is a simplified illustration of the experimental apparatus. The .50 caliber ogive projectiles were saboted in a thin wall, two piece, copper jacket crimped to the projectile. The sabot was stripped aerodynamically before impact. The projectiles were launched with chemical propellent in a smooth bore gun.

The velocity of the projectile before impact was determined from the time of flight between two photographic stations. The projectile orientation and velocity after perforation of the target material were determined from two x-radiographs. The x-radiograph stations were separated along the exit trajectory and the fields of view of the two x-radiographs were perpendicular to each other, providing determination of the yaw and pitch of the projectile (refer to Figure 3). The velocity was determined from the time of flight between the two stations. The accurate determination of the initial and residual momentum of the projectile from the initial and residual velocities provided verification of momentum transfer to the pendulum structure.

The chord of pendulum motion after impact was measured from a photograph of the path of an illuminated silvered wire marker attached to the pendulum as shown in Figure 4. A stationary scale placed behind the wire in the field of view of the camera facilitated accurate determination of the chord from the photograph.

# SECTION IV

# RESULTS

The data collected on momentum transfer to the blade material is grouped according to impact conditions and material in Table 1. All targets were 3.18 mm thick and nominally 152 mm square.

The oblique impacts were divided into two, those in which the plate faced "up" in the pendulum and those in which it faced "down". No significant difference in the momentum transfer was detected.

Figure 5 shows the percentage of the initial momentum transferred to the pendulum versus impact velocity, and Figure 6 shows the amount of momentum transferred to the pendulum versus the impact velocity.

As shown in Figure 6 the momentum transfer is nearly independent of velocity for graphite/epoxy and for titanium at 90°. However, titanium at 60° shows a decline in momentum transfer with increasing velocity. If the low velocity point was close to the ballistic limit, the additional momentum transfer could be accounted for. In general, the data is inconsistent. From Figure 5, the momentum transfer at 488 m/s for the various conditions tested is shown in Table 2.

The 90° impact results compare favorably with the analytic results shown in Figure 7 taken from a CRT monthly report. Realistic titanium corresponding to Ti 6-4 shows a momentum transfer of 10%. "Brittle" titanium which has less contact time with the projectile absorbed less momentum (6.8%). The boron-aluminum composite material absorbed 2.9% and the graphite-epoxy composite absorbed 1.8%. The measured momentum transfer compares within experimental error with the calculations for B-Al, but is low for graphite-epoxy and "realistic" Ti 6-4. These differences may reflect the variation of materials properties with strain rate and could be explained if both Ti 6-4 and graphite-epoxy became more brittle at high strain rates.

The 60° impact calculation as shown in Figure 8 indicates a momentum

# TABLE 1

## SHOT DATA

| SHOT NO. | TARGET | PROJECTILE MASS (g) | PROJECTILE VELOCITY INITIAL (m/s) | PROJECTILE MOMENTUM INITIAL (kg-m/s) | PROJECTILE VELOCITY RESIDUAL (m/s) | PROJECTILE MOMENTUM RESIDUAL (kg-m/s) | PROJECTILE CHANGE IN MOMENTUM (kg-m/s) | PROJECTILE CHANGE IN MOMENTUM (%) | PENDULUM MOMENTUM (kg-m/s) | PENDULUM MOMENTUM (%) | TARGET ORIENTATION |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 54 | TI 6-4 90° to trajectory | 19.1 | 338 | 6.46 | --- | --- | --- | --- | .67 | 10.3 | |
| 55 | | 19.4 | 347 | 6.70 | --- | --- | --- | --- | --- | --- | |
| 56 | | 19.2 | 453 | 8.69 | 418/403 | 5.97/1.96 | 0.76 | 8.7 | .71 | 8.2 | |
| 45 | TI 6-4 60° to trajectory | 19.0 | 479 | 9.09 | --- | --- | --- | --- | 1.00 | 11.0 | UP |
| 46 | | 19.3 | 323 | 6.24 | 212 | 5.15 | 2.14 | 34.3 | 1.27 | 20.3 | UP |
| 50 | | 19.1 | 492 | 9.40 | 428/394 | 5.61/2.36 | 1.43 | 15.2 | --- | --- | DOWN |
| 51 | | 19.4 | 475 | 9.22 | --- | --- | --- | --- | 1.07 | 11.6 | DOWN |
| 53 | | 19.3 | 501 | 9.66 | 441/388 | 5.38/2.76 | 1.52 | 15.7 | .97 | 10.0 | DOWN |
| 47 | Graphite Epoxy 90° to trajectory | 19.3 | 459 | 8.85 | --- | --- | --- | --- | .095 | 1.07 | |
| 48 | | 19.3 | 498 | 9.59 | 488 | 9.42 | 0.17 | 1.8 | .095 | .99 | |
| 49 | Graphite Epoxy 60° to trajectory | 19.3 | 487 | 9.38 | --- | --- | --- | --- | .124 | 1.32 | DOWN |
| 57 | | 19.2 | 517 | 9.92 | 502 | 9.64 | 0.28 | 2.8 | .127 | 1.28 | UP |
| 58 | BoAl 90° to trajectory | 19.4 | 507 | 9.84 | 447 | 8.67 | 1.17 | 11.9 | .290 | 2.94 | |

## TABLE 2

### EXPERIMENTAL RESULTS - MOMENTUM TRANSFER IN % FOR .50 CAL OGIVE IMPACT

| | Ti 6-4 | Graphite Epoxy | BAl |
|---|---|---|---|
| 90° | 7.6 | 1.0 | 3.0 |
| 60° | 10.8 | 1.3 | |

very nearly the same as for the 90° impact on Ti 6-4. The experiments indicate a significantly higher transfer. This lack of agreement is most likely due to the assumptions necessary to conduct oblique impact calculations with the two dimensional code. As these problems in the code are attacked, improved agreement can be expected.

All the projectiles impacted on Ti 6-4 broke, with the exception of the low velocity shot (#54). (A collection of the x-radiographs of the projectiles is contained in Appendix A). The effect of projectile breakage in momentum transfer is not known although there was some evidence that the projectile did not break until late in the impact or after impact. The holes in the plates were all round and it required some force to insert an undeformed projectile through the hole.

The difference between the initial and measured residual projectile momentum is, as expected, higher than the pendulum momentum; the discrepancy is due to the momentum carried away by the target debris. The residual momentum data is tabulated in Table 3. The debris mass was assumed to consist of a disk of material 1.27 cm in diameter and 3.18 mm thick. The velocities calculated are those necessary for the debris to account for the additional momentum lost by the projectile. There is considerable uncertainty in the residual momentum for the shots in which the projectile broke and each fragment must be measured. The remaining data also presents some difficulties, in particular the very high debris momentum and velocity for

B-A1. However, there is insufficient repetition to draw any firm conclusions on residual momentum from this data.

# TABLE 3

## RESIDUAL MOMENTUM DATA

| SHOT NO. | TARGET MATERIAL | IMPACT ANGLE (°) | IMPACT VELOCITY (m/s) | DEBRIS MASS (g) | DEBRIS MOMENTUM (kg-m/s) | DEBRIS VELOCITY (m/s) |
|---|---|---|---|---|---|---|
| 56 | Ti 6-4 | 90° | 433 | 1.83 | 0.06* | 33 |
| 46 | Ti 6-4 | 60° | 323 | 1.83 | 0.87 | 475 |
| 53 | Ti 6-4 | 60° | 501 | 1.83 | 0.55* | 300 |
| 48 | Graphite Epoxy | 90° | 498 | 0.72 | 0.08 | 110 |
| 57 | Graphite Epoxy | 60° | 517 | 0.72 | 0.15 | 212 |
| 58 | B-Al | 90° | 507 | 1.08 | 0.88 | 815 |

*Projectile broken during impact.

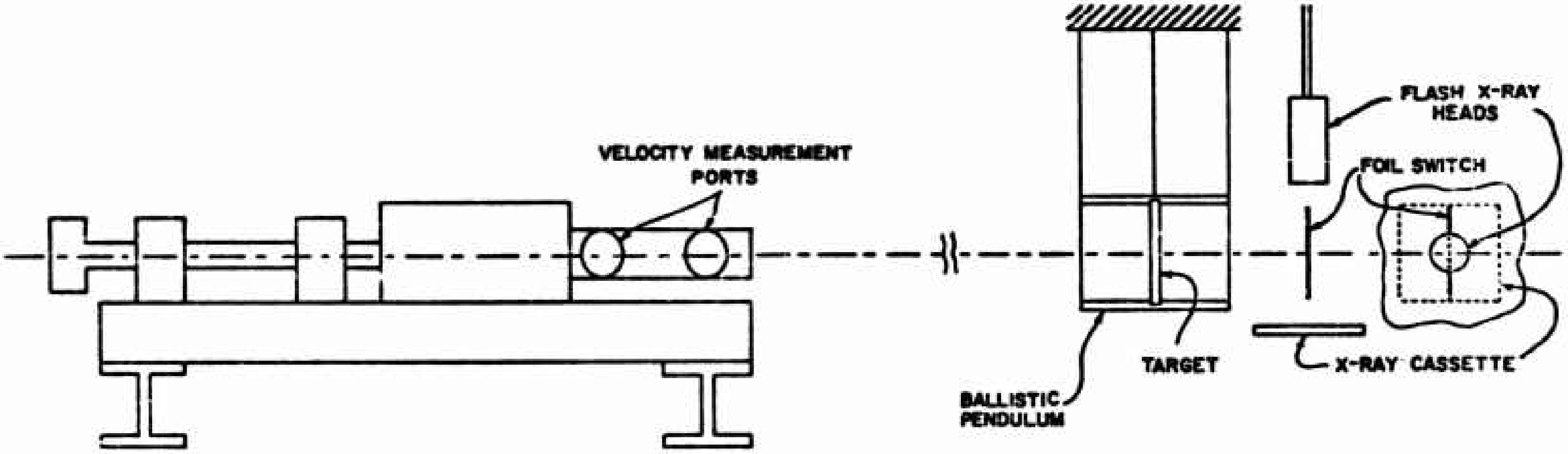


Figure 3. A Schematic of the Ballistic Range Showing the Experimental Apparatus Used.

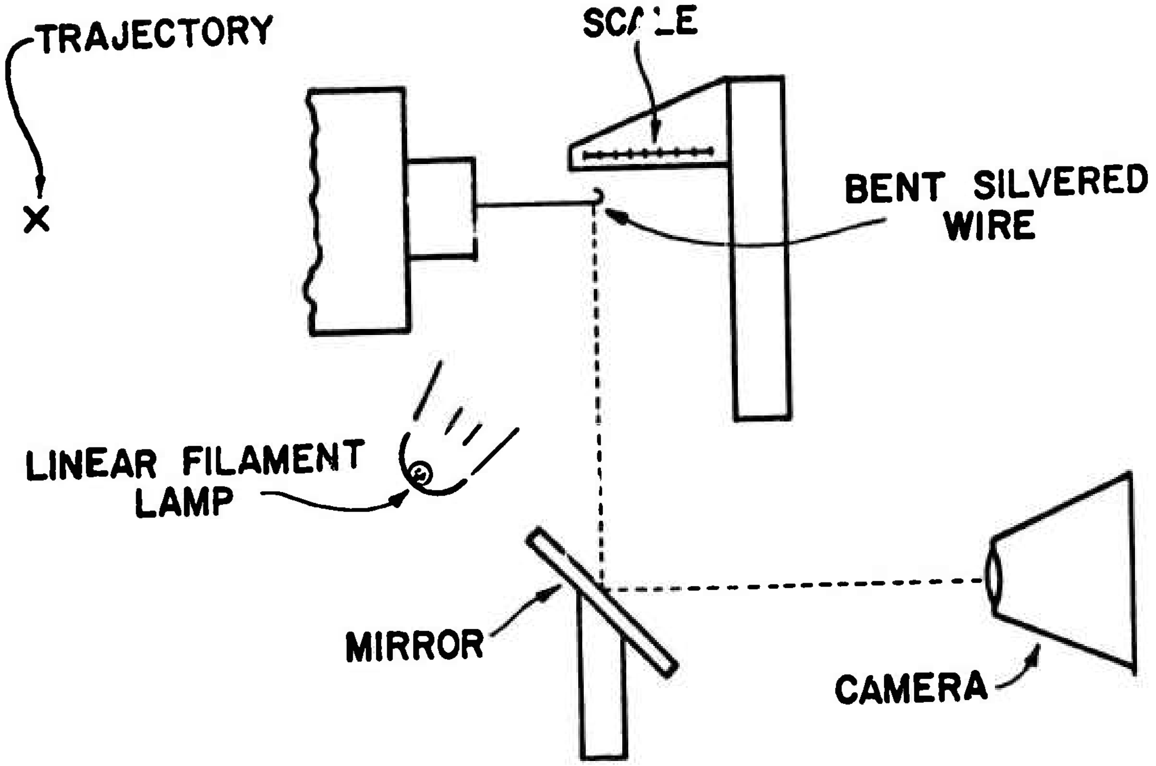


Figure 4. A Schematic of Silver Wire Marker and Illuminated Scale.

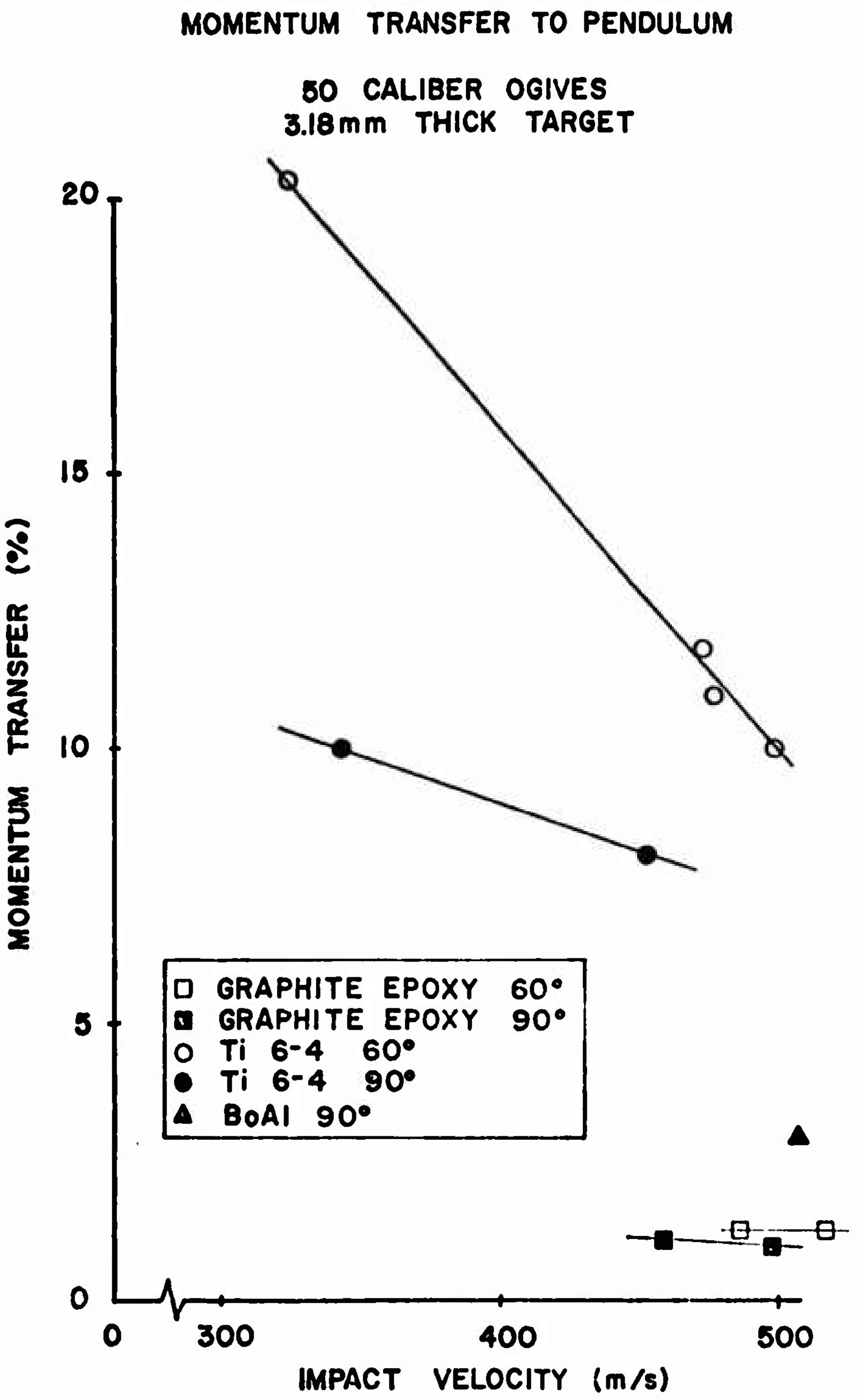


Figure 5. A Graph of Percentage Momentum Transfer to the Blade Material Versus Impact Velocity of the Projectile.

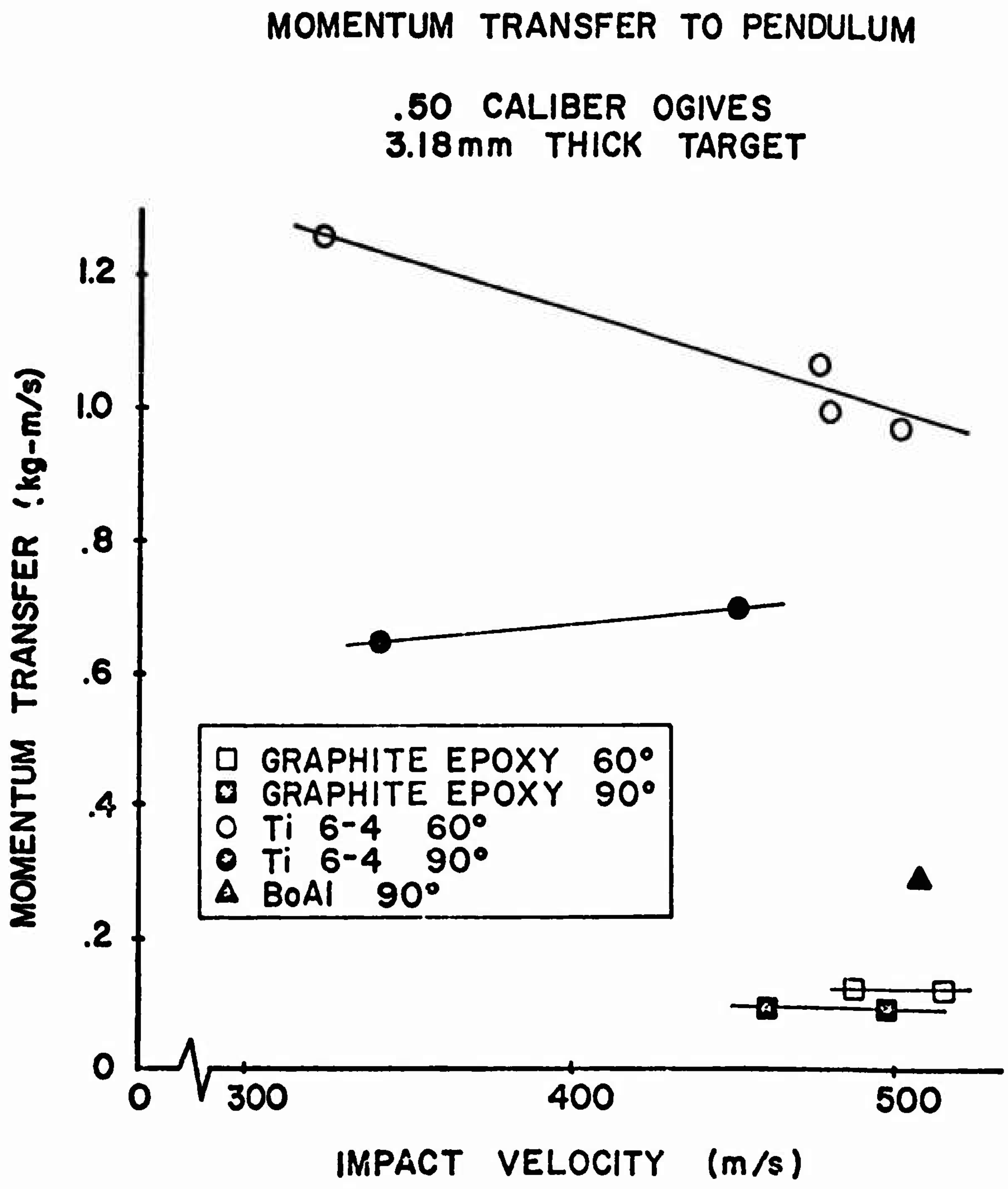


Figure 6. A Graph of Momentum Transfer to the Blade Material Versus Impact Velocity of the Projectile.

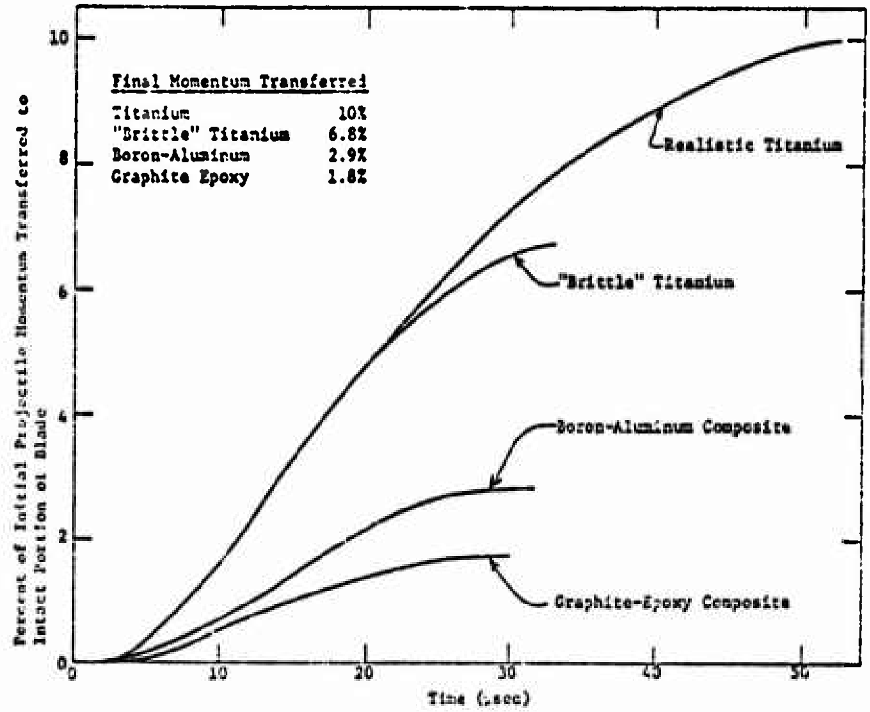
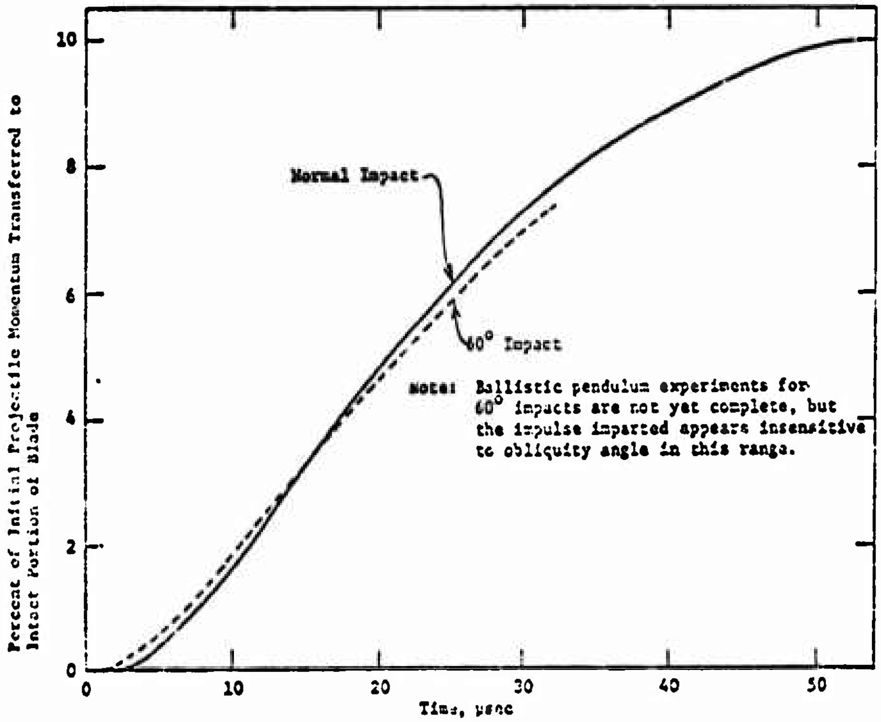


Figure 7. Comparison Showing Transfer of Projectile Momentum to Different Blade Materials by 488 m/s Normal Impact of .50-cal. Projectile.

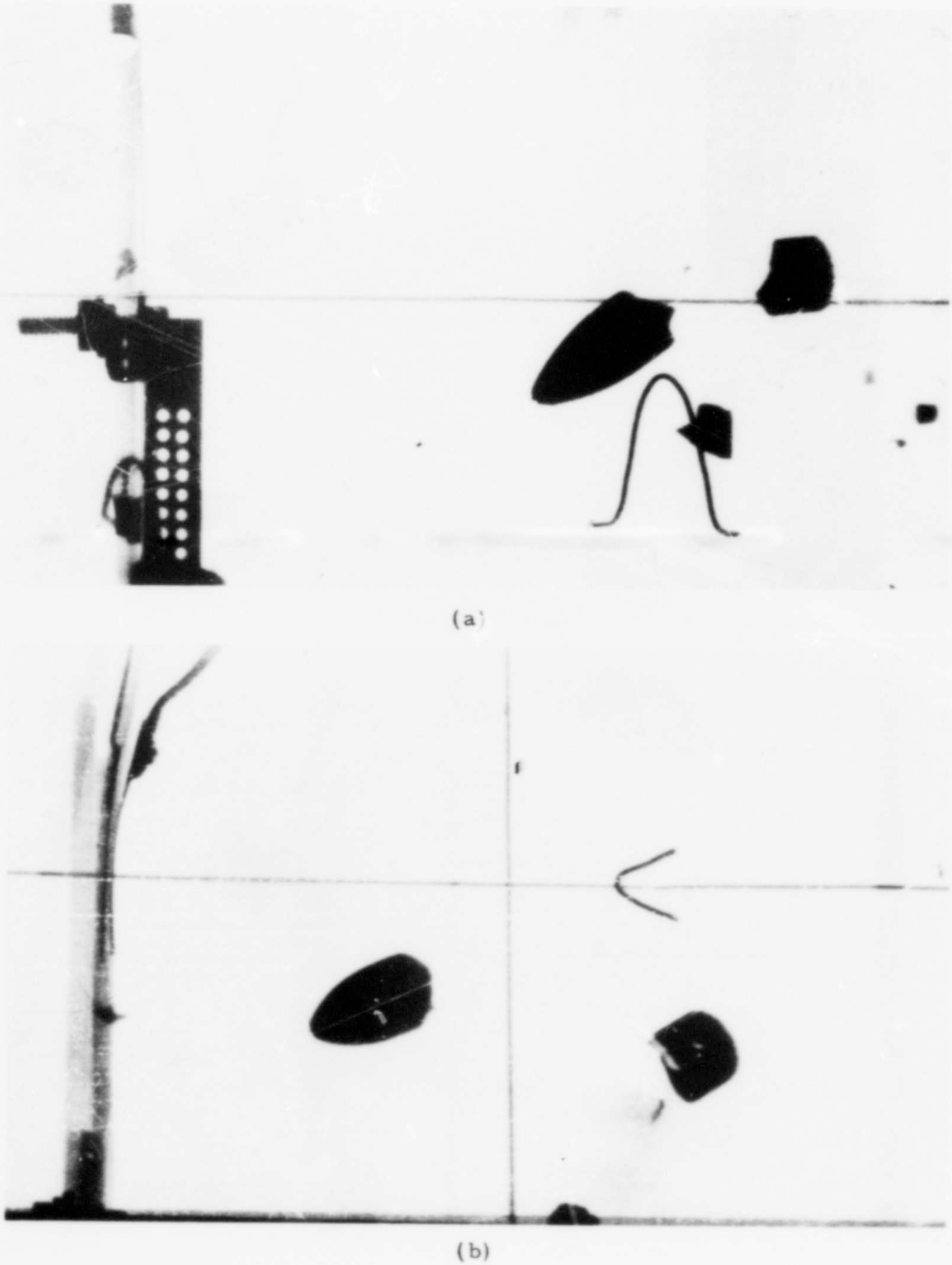


Note: Ballistic pendulum experiments for 60° impacts are not yet complete, but the impulse imparted appears insensitive to obliquity angle in this range.

Figure 8. Comparison Showing Transfer of Projectile Momentum to Titanium Blades During Normal and 60° Oblique Impacts of .50-cal. Projectile at 488 m/s.

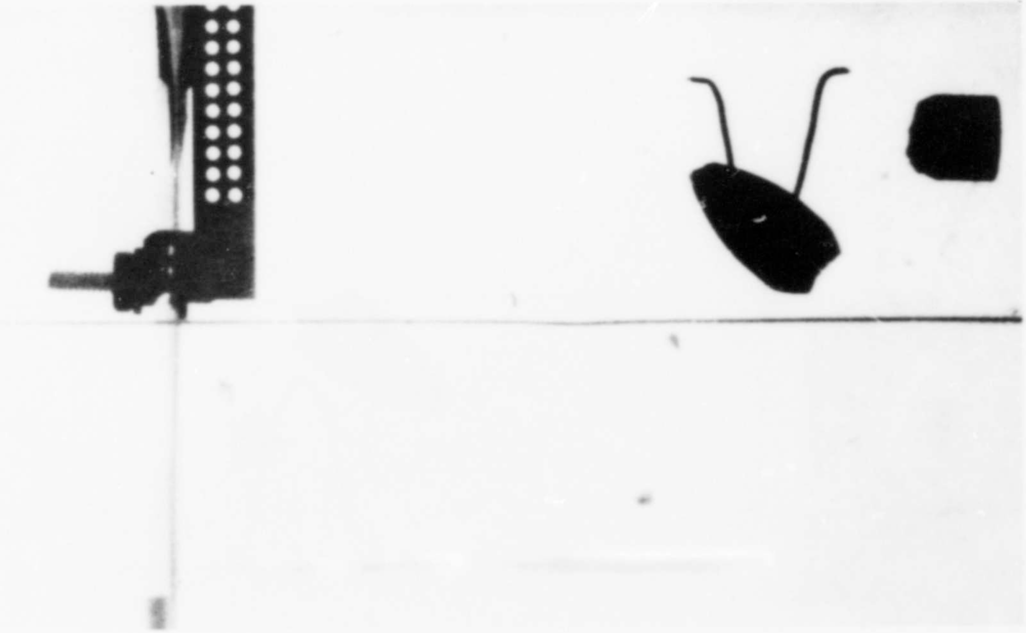
# APPENDIX A

## X-Radiographs of Residual Projectiles

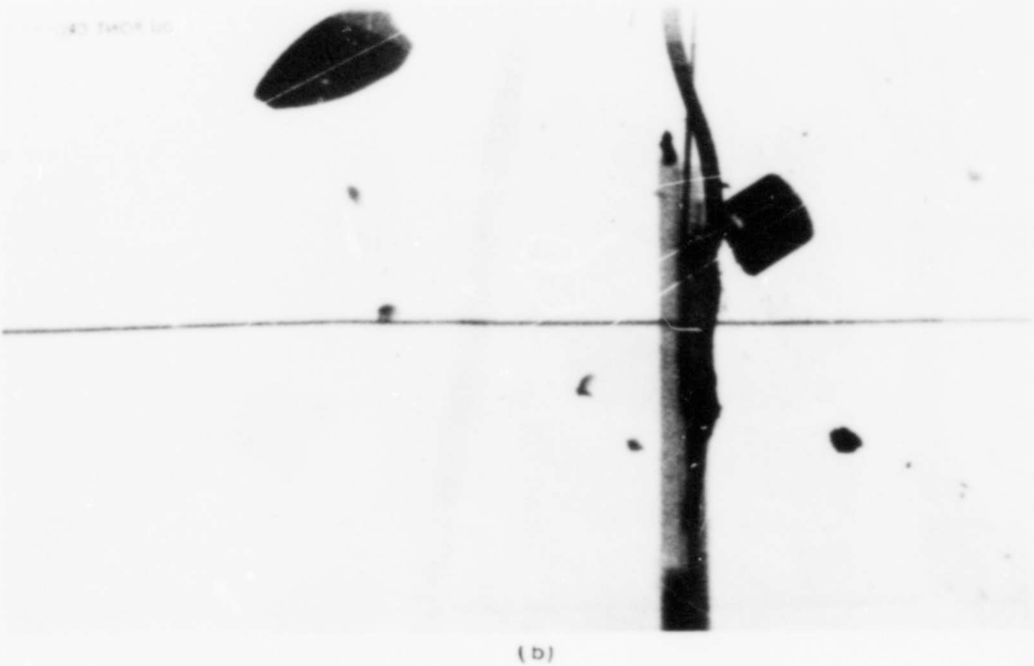


Shot 50 Projectile: 19.3 mm hardened steel ogive
Target: 3.18 mm Ti 6-4, 60° to trajectory
Impact velocity: 492 m/s

(a) vertical; (b) horizontal



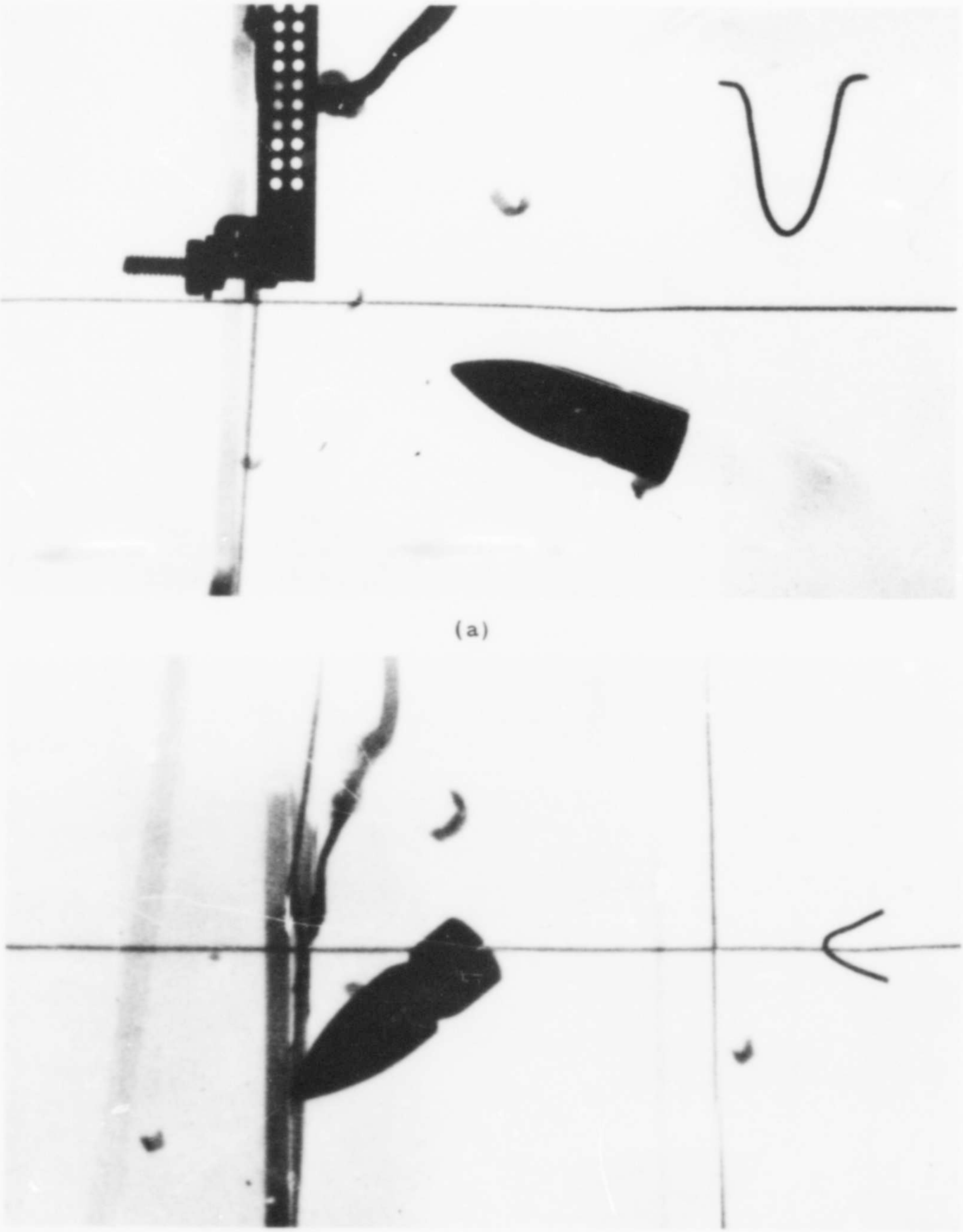
(a)



(b)

Shot 53 Projectile: 19.3 mm hardened steel ogive
Target: 3.18 mm Ti 6-4, 60° to trajectory
Impact velocity: 501 m/s

(a) vertical; (b) horizontal

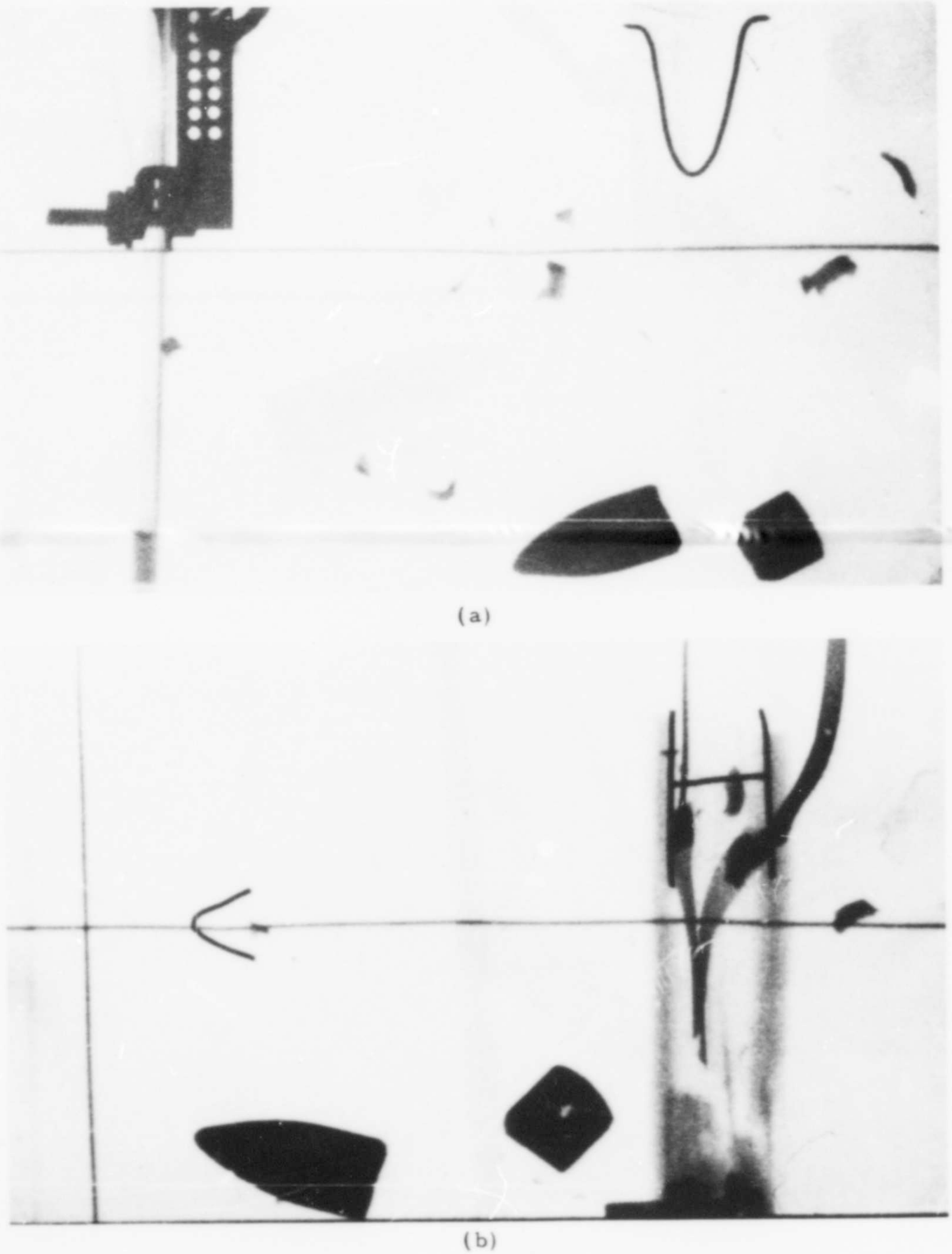


(a)

(b)

Shot 54 Projectile: 19.1 mm hardened steel ogive
Target: 3.18 mm Ti 6-4, 90° to trajectory
Impact velocity: 341 m/s

(a) vertical; (b) horizontal



(a)

(b)

Shot 55 Projectile: 19.3 mm hardened steel ogive
Target: 3.18 mm Ti 6-4, 90° to trajectory
Impact velocity: 347 m/s

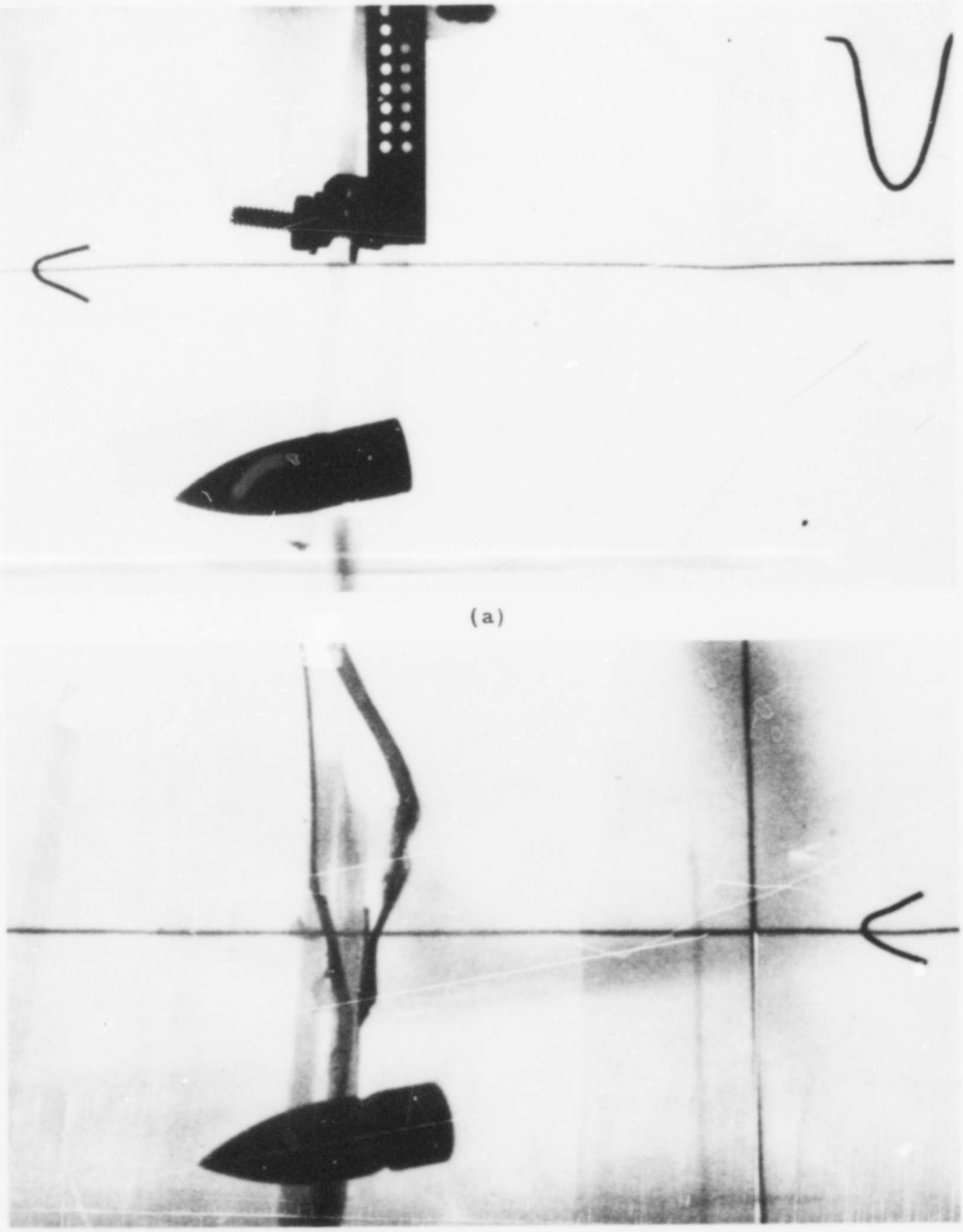
(a) vertical; (b) horizontal

(a)

(b)

Shot 56 Projectile: 19.2 mm hardened steel ogive
Target: 3.18 mm Ti 6-5, 90° to trajectory
Impact velocity: 453 m/s

(a) vertical; (b) horizontal

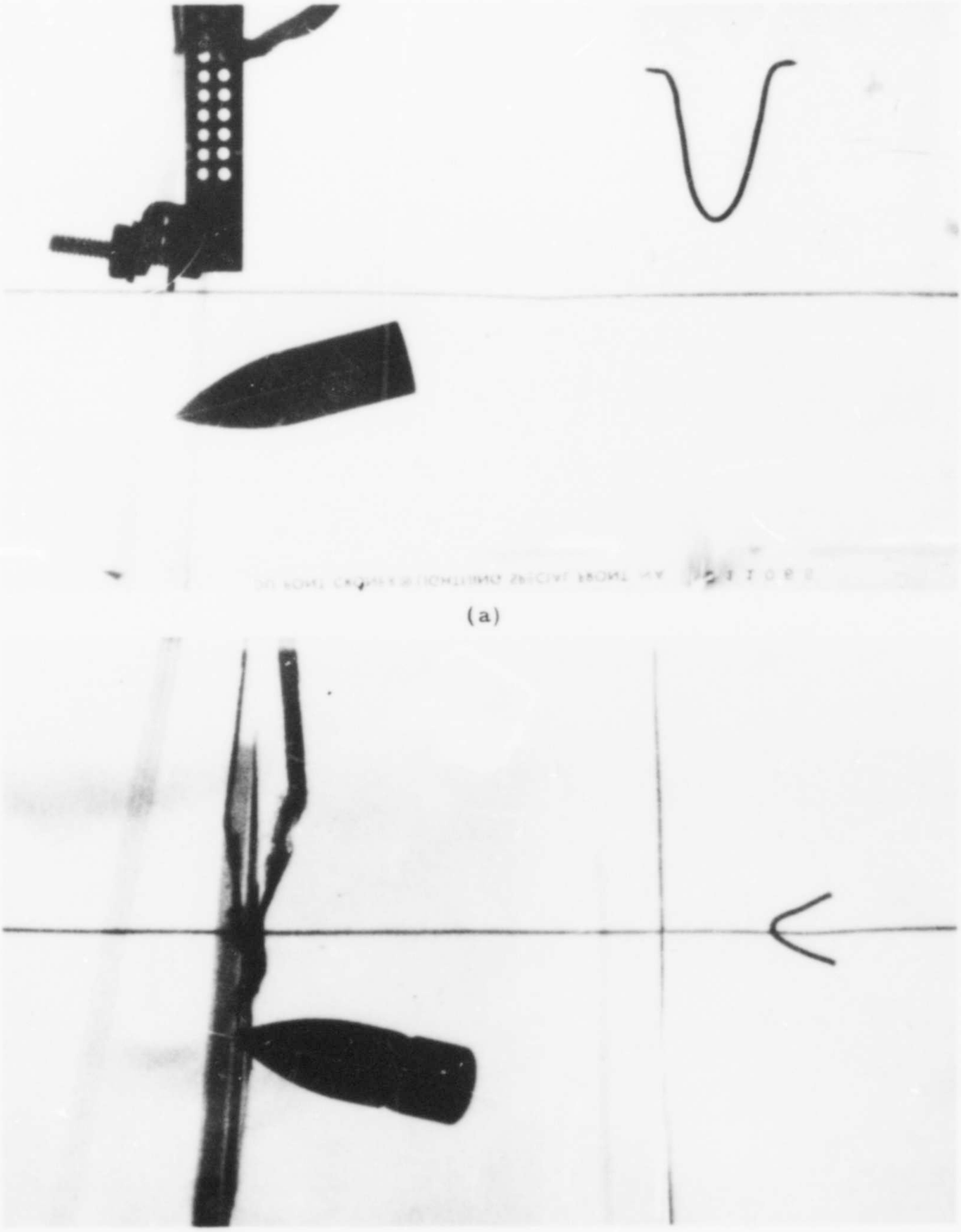


(a)

(b)

Shot 57 Projectile: 19.2 mm hardened steel ogive
Target: 3.18 mm Graphite-epoxy, 60° to trajectory
Impact velocity: 517 m/s

(a) vertical; (b) horizontal



(a)

(b)

Shot 58 Projectile: 19.4 mm hardened steel ogive
Target: 3.18 mm B-Al, 90° to trajectory
Impact velocity: 507 m/s

(a) vertical; (b) horizontal