LABORATORY TESTING OF LONG ROD PENETRATOR AND SABOT COMPONENTS

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ABSTRACT

Laboratory testing apparatus is described which can be used to simulate the launch loading of penetrator and sabot components from kinetic energy penetrator rounds. Load and deflection to failure of production components has been measured and compared for different materials and configurations.

Results are described from penetrators made from a uranium alloy and two tungsten alloys. Results from sections of sabots are described, including two aluminum alloys and different configurations.

INTRODUCTION

A kinetic energy penetrator is, in basic form, a rod with a high length-to-diameter ratio which is manufactured from high density material and launched from a gun tube. The launching is achieved by mechanically coupling the penetrator to a sabot, which fits the gun tube bore diameter, and which is discarded upon exit from the gun tube. Figure 1 shows a photograph of a typical kinetic energy projectile, Figure 1a, along with a sketch of the basic components and loading of the projectile, Figure 1b. The firing pressure on the sabot causes high acceleration of the projectile, and this leads to the classic F = ma type of loading. Particularly near the junction of the unsupported sections of the penetrator with the sabot, high axial normal stresses develop in the penetrator and high shear stresses develop in both components. The tensile stresses at the rear of the penetrator are of particular concern here, because they could lead to a brittle fracture of a penetrator during launch. Such a failure occurred early in the development of Army kinetic energy penetrator rounds at the rear of the interconnection between sabot and penetrator. Figure 2 shows the mechanical interconnection, a series of lugs and grooves, in detail. They are termed lugs because they have no helix advance as in a thread. The profile of the lug is that of a buttress thread which has long proven its ability to transmit load in a single axial direction. The lugs and grooves act as stress concentrators for the body forces and lug forces which are applied by the sabot. A laboratory test that could simulate the lug loading, and also apply tensile stresses to a finish-machined penetrator would allow the structural integrity of the penetrators to be determined at a lower cost and in a shorter time than would firing tests. In addition, load, deflection, and failure mechanism information can be determined in the laboratory tests, whereas such information generally cannot be obtained from firing tests. This report describes a laboratory launch-simulation test system for kinetic energy projectiles. It describes test results from uranium and tungsten penetrators and from two aluminum alloys for sabots. In addition, the load carrying capability of the buttress lug profile was investigated by loading to failure sabot sections with varying numbers of lugs.

Figure 1a Typical Kinetic Energy Penetrator Round With One Sabot Section Removed

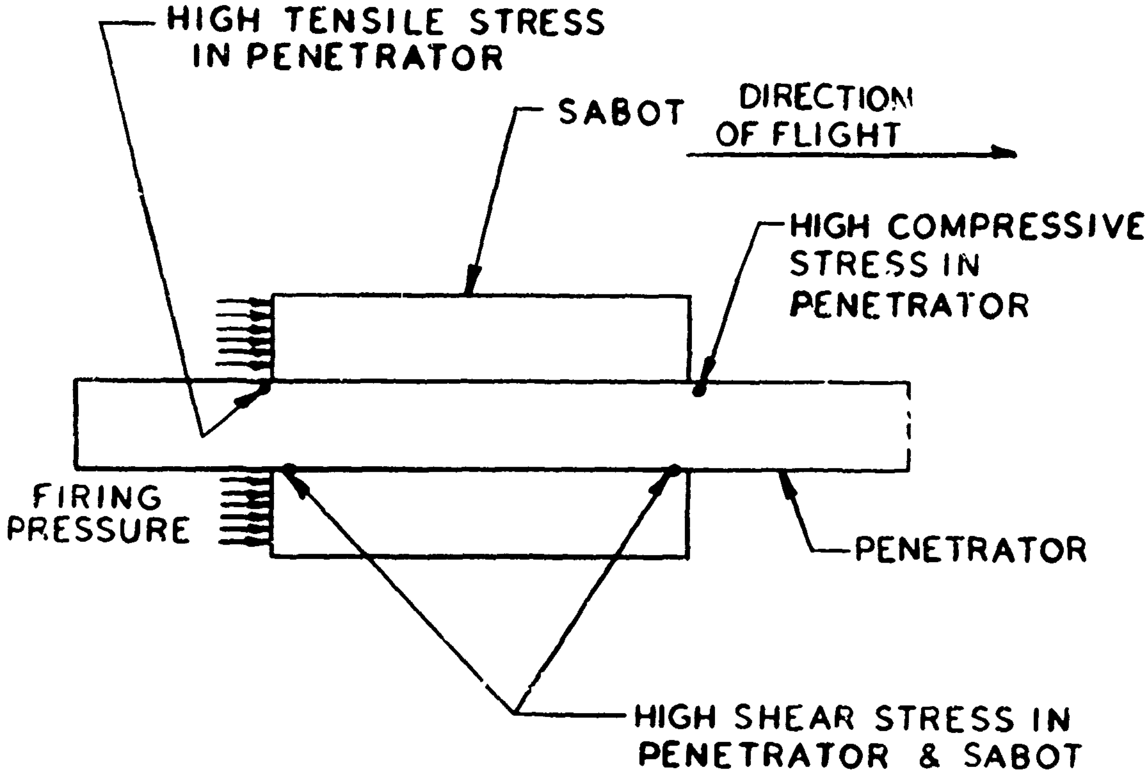


Figure 1b Sketch of Typical Kinetic Energy Penetrator

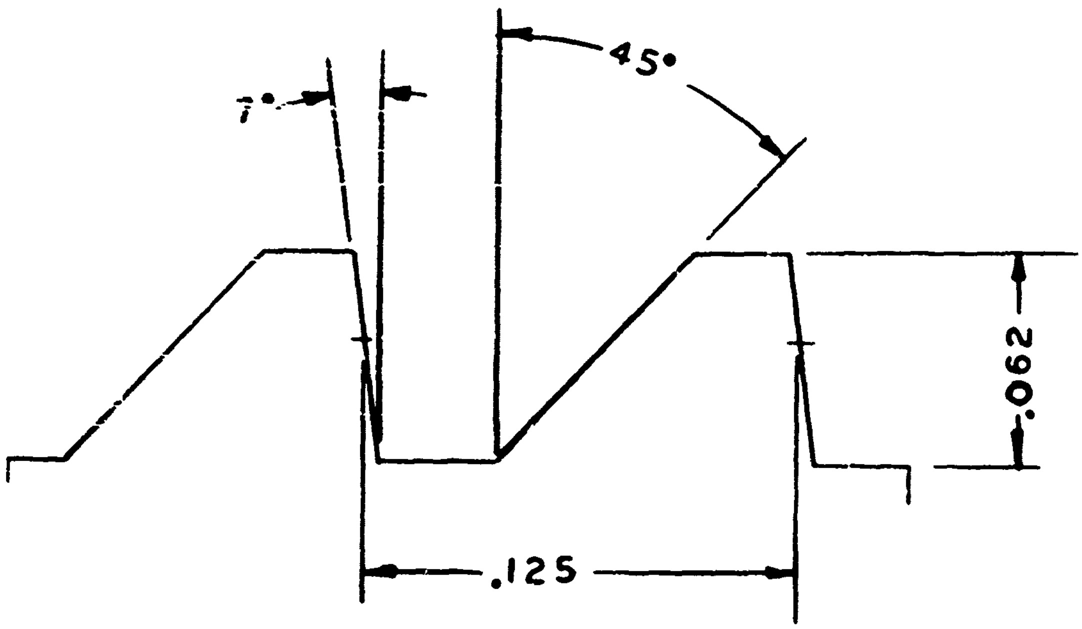


Figure 2 Sketch of Lug Profile

SIMULATION TEST APPARATUS

The launch simulation test equipment was described in a prior report [1]. A few details are given here. Figure 3 is a photograph of the simulation test equipment capable of applying 200,000 lbs. of tensile load to a penetrator or a sabot section. The hydraulic cylinder mounted on the base moves a load frame assembly as a unit. The tensile load is applied between the movable upper load frame (small columns) and the stationary lower load frame (large columns). The load is applied to the specimen assembly (not shown) through the rods and end caps shown near the top of the photograph. A 200,000 lb. load cell mounted between the hydraulic cylinder and upper load frame provides the load measurements.

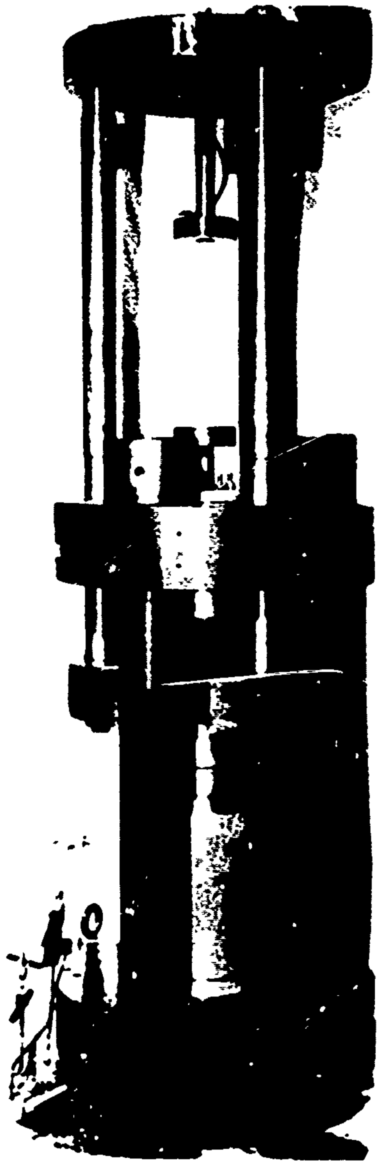


Figure 3 Two Hundred Thousand Pound Launch Simulation Test System For Kinetic Energy Penetrator Rounds

Figure 4 shows the specimen assembly which is mounted in the simulation equipment. The loading rods and end caps apply the tensile load through the fixture to the sabot segments. The forward sabot segment (on the right) transmits the load to the thread-like lugs on the penetrator in the same general way as in the launch of the projectile, the load being applied to the 7° faces of the lugs. The rear sabot segment is loaded on the 45° face and in the direction opposite to that of launch. Figure 5 shows this in more detail. Based on the work of Pflegl et al [2] the concentrated stress at the root of the lug fillet is expected to be lower when the lug is loaded on the 45° face than when it is loaded on the 7° face. In simplified concept, the reason for the lower fillet stress is that the radial compressive component of the force on the penetrator is much larger for the 45° face than for the 7° face. This compressive force tends to lower the tensile fillet stress, so that any failure of the penetrator would be expected at the fillet of the first forward loaded lug on the penetrator, point A shown in Figure 5.

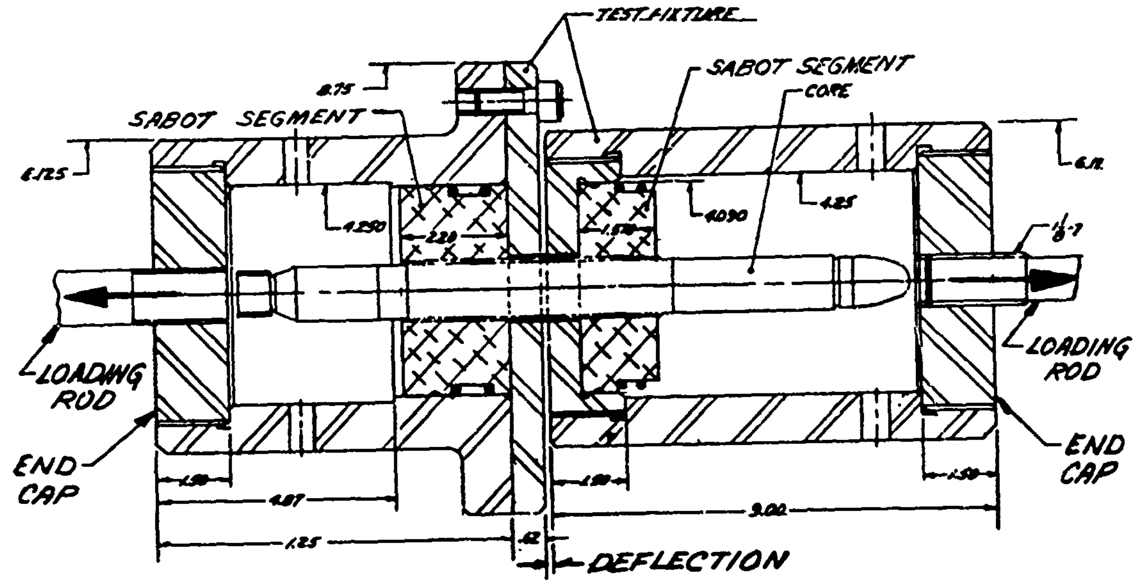


Figure 4 Specimen Assembly For Launch Simulation Test System

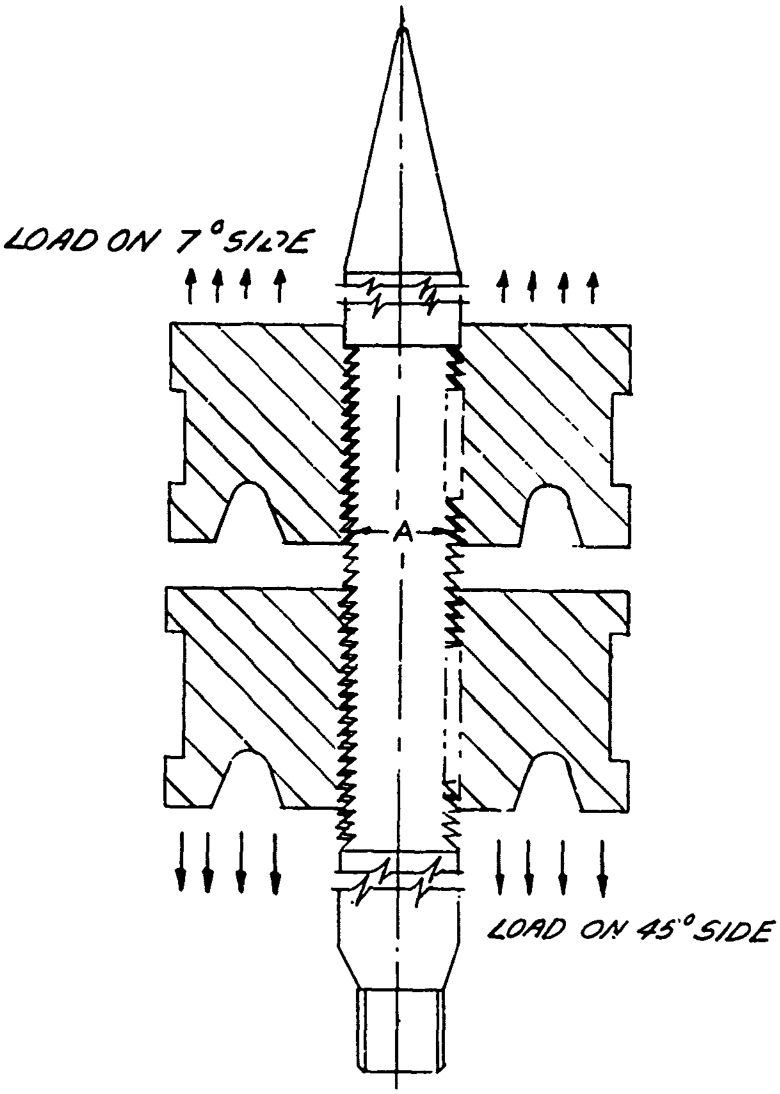


Figure 5 Sketch of Tensile Loading of Complete Penetrator Using Segments of Sabots

PENETRATOR TEST RESULTS

The loading of a penetrator through sabot segments causes a tensile stress field in the penetrator which is concentrated by the lugs and grooves. The lugs are also directly loaded. This combined loading of the penetrator is the same type as that during launch. Further, by using a finish-machined penetrator the same stress concentration factor is obtained in the laboratory as that in service. Table I presents the data for tensile failure of full size penetrators tested in the lug loaded condition using maraging steel sabot segments. Also shown in Table I are typical yield and ultimate tensile strengths for the materials from manufacturers data. The depleted uranium-.75 percent titanium alloy is a solution treated and aged material with nominal solution treatment and aging temperatures of 800-850°C and 350°C respectively. The tungsten materials are proprietary commercial alloys produced using powder metallurgy processes. The average stress at failure is close to the ultimate strength of the material in the cases of the uranium and 90 percent tungsten materials; whereas the 97 percent tungsten failed at a somewhat lower level of stress relative to its ultimate strength. The test specimens were 1.02 in. (26 mm) in diameter with .062 in. (1.6 mm) grooves, as in Figure 2. Some specimens were complete penetrators, as shown in Figures 4 and 5; some were grooved sections only. For the purposes of the test here, there was no difference. The failure appearance of the 90 percent tungsten and uranium materials were typically flat failure surfaces across the root of the lug as shown in Figure 6. The 97 percent tungsten material, rather than failing by a flat break across the root of the lug, failed in cup and cone fashion as shown in Figure 7. In the cup section a crack was seen at the root diameter coinciding in depth with the bottom of the cup. In addition, cracks were noted at adjacent lug roots. The additional cracking suggests that as the failure load is approached, cracks initiate at the lug roots and one crack grows to critical size and results in failure.

Figure 8 shows the load deflection curves for the three penetrator materials studied. The deflection measured is that shown in Figure 4 and is the result of all the elasticity in the system not just the elongation of the penetrator material. However, the slopes of the lines are generally indicative of the elastic moduli of the material; uranium has the lowest modulus and the lowest slope, and so forth. The plastic deformation shown for the 90 percent tungsten and uranium materials indicate their notch toughness in comparison to the 97 percent tungsten material which shows virtually none. The important implications of this measure of notch toughness will be discussed further in Summary and Conclusions.

TABLE I. Tensile Failure Load of Penetrators of Three Materials

Material	Material Strength; ksi (MPa)		Load to Failure; k lb. (kN)	Average Stress to Failure; ksi (MPa)	Failure Stress as a % of Ultimate Stress
Uranium-0.75% Titanium	Yield	120 (827)	156 (694)		
			157 (699)		
	Ultimate	210 (1448)	154 (685)	189 (1303)	90%
			154 (685)		
Tungsten-3% Binder	Yield	166 (1145)	98 (436)		
	Ultimate	167 (1151)	98 (436)	119 (820)	71%
Tungsten-10% Binder	Yield	- -	154 (685)	189 (1303)	107%
	Ultimate	176 (1214)	155 (690)		

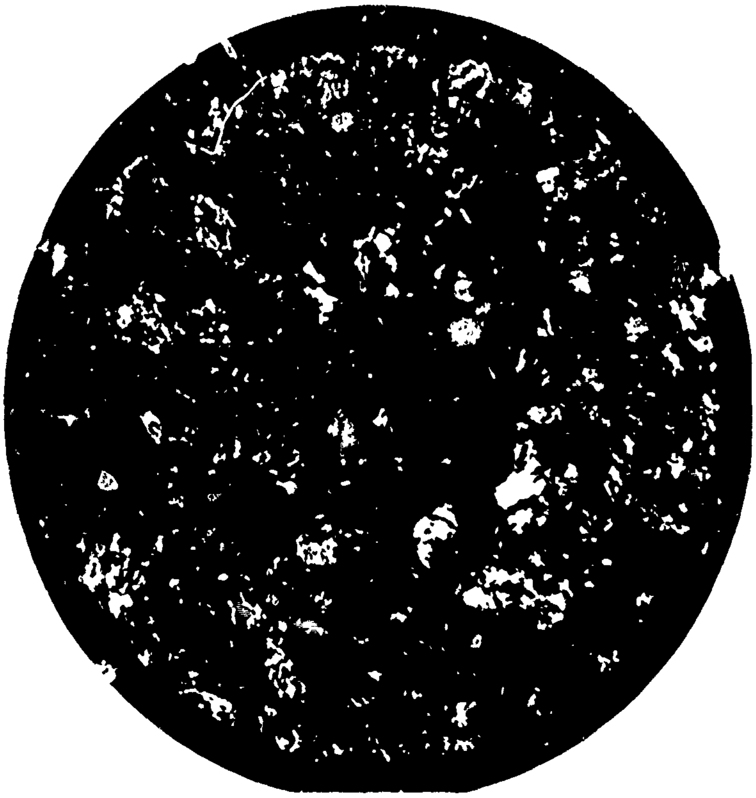


Figure 6 Macrophotograph of Fracture Surface of Uranium Penetrator at Root of Rearmost of Loaded Lug

Figure 7 Macrophotograph of Fracture Surface of 97 Percent Tungsten Penetrator at Root of Rearmost Loaded Lug

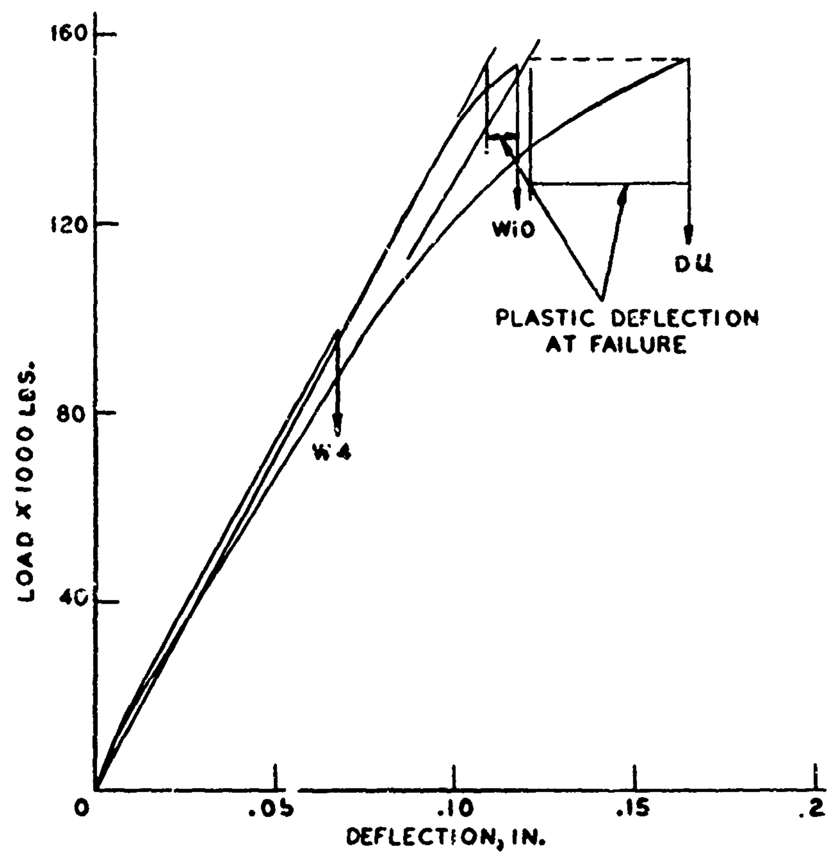


Figure 8 Load Deflection Curves For Three Penetrator Materials

Table II presents the results of notched tension tests conducted on 90 percent tungsten material. Smooth specimens having a diameter of .250 in. (6.4 mm) were tested and compared with notched specimens with .375 in. (9.5 mm) outer diameter, .250 in. (6.4 mm) notch diameter, and .0075 in. (0.19 mm) root radius, 60° notch. The results show the material to be notch ductile, because the failure stress of notched specimens was greater than that of the unnotched specimens, significantly greater in this case, 138 percent on average. Also, it should be noted that the average ultimate tensile strength of the unnotched specimens, 168 Ksi (1158 MPa), is in good agreement with the average manufacturers result from the center of the penetrator blanks, 167 Ksi (1151 MPa).

TABLE II. Failure Stress of Notched and Unnotched 90% Tungsten Tension Specimens; 0.25 in. (6.4 mm) Diameter

Unnotched		Notched	
ksi	(MPa)	ksi	(MPa)
169	(1165)	224	(1545)
167	(1152)	232	(1601)
		230	(1587)
		246	(1699)
		230	(1587)

SABOT TEST RESULTS

ALLOY COMPARISON

Sabot sections were made from 7075 T6 and 7075 T73 aluminum alloy; the T6 condition is that used for sabots and the T73 condition is under consideration because of its increased resistance to stress corrosion cracking. The sections have a basic inner diameter of 1.02 in. (26 mm), have 11 lugs, a length of 1.38 in. (35 mm), and a shear area of 3.45 in.^{2} (2230 mm^2). Table III presents the data obtained when testing these sections with a 250 maraging steel penetrator as previously described in relation to Figures 3 and 4. The short transverse orientation was tested, that is, the shear plane in the tests was normal to short transverse direction, which is the radial direction for sabot segments. As expected the T73 material fails at a lower load. The average failure load and corresponding shear stress for the T73 tests was 89 percent of that of the T6 tests. This is in reasonable agreement with the comparison of ultimate shear strengths, in which the strength for T73 is 85 percent of that for the T6 material. Comparison of the data in Table III shows the T73 failure to be slightly less variable; additional testing would be required to determine if this is generally true. This consistency would of course help in a statistical determination of acceptable strength. Figure 9 is a load vs. deflection curve for sabot sections of T73 and T6 material. The T73 exhibits some increase in ductility which also may be a help in the present application.

TABLE III. Shear Failure of Lugs of Aluminum Sabot Section; Short Transverse Orientation

Material	Ultimate Strength in Shear, ST Orientation; ksi (MPa)	Load to Failure k lb. (kN)	Average Shear Stress at Failure ksi (MPa)
7075-T6 Aluminum	43.4 (299)	144 (641) 151 (672) 145 (645)	42.5 (293)
7075-T73 Aluminum	40.3 (278)	131 (583) 130 (579) 131 (583)	37.8 (261)

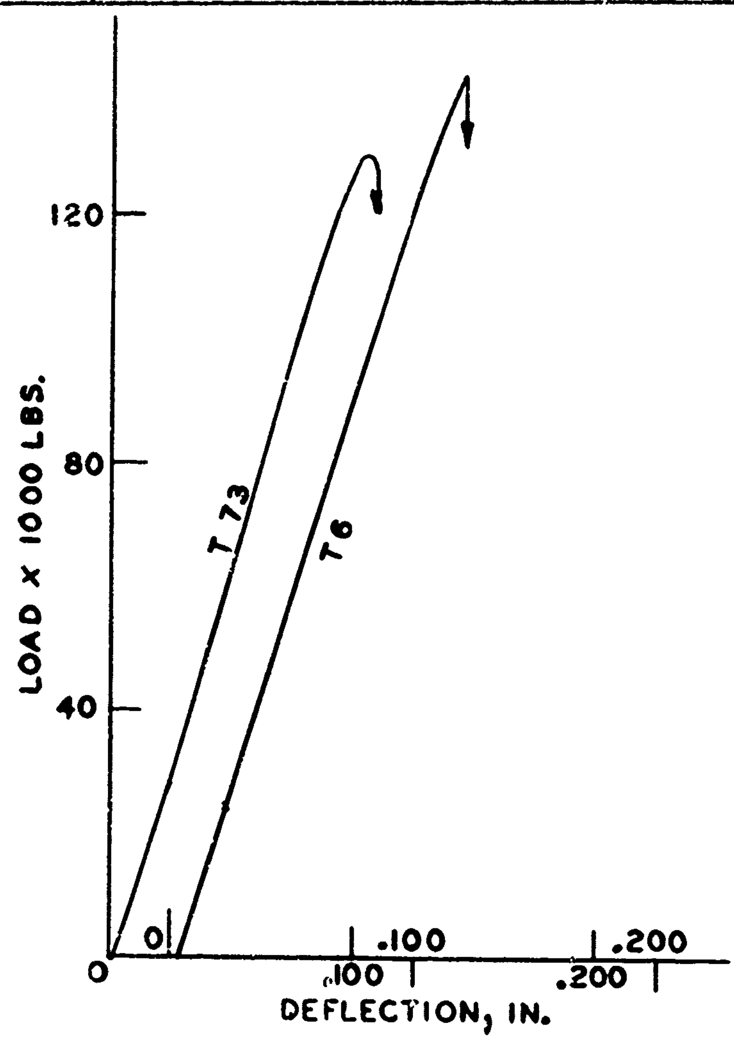


Figure 9 Load Deflection Curves For Two Sabot Materials

SHEAR AREA COMPARISON

Figure 10 shows the results of testing 7075 T6 alloy sabot sections of various lengths. The sabot sections had 11, 8, and 5 lugs; lengths of 1.38 in. (35 mm), 1.00 in. (25 mm), and 0.63 in. (16 mm); and shear areas of 3.45 in.^{2} (2230 mm^2), 2.50 in.^{2} (1610 mm^2), and 1.55 in.^{2} (1000 mm^2), respectively. The plotted points are the three tests conducted for each case and the line is calculated from the measured ultimate shear strength of the T6 material in Table III. The shear strength was measured in the short transverse orientation so that the failure would occur in the same plane as in service conditions; the measurement of shear strength was made according to ASTM Method B565-76. Figure 11 shows the direction in which the shear specimen was taken from a sabot segment and also the test fixture used to generate the strength data. The experimental results are in good agreement with the expected result in Figure 10. This indicates that no one lug will fail until they all fail in unison at about the ultimate shear strength of the material.

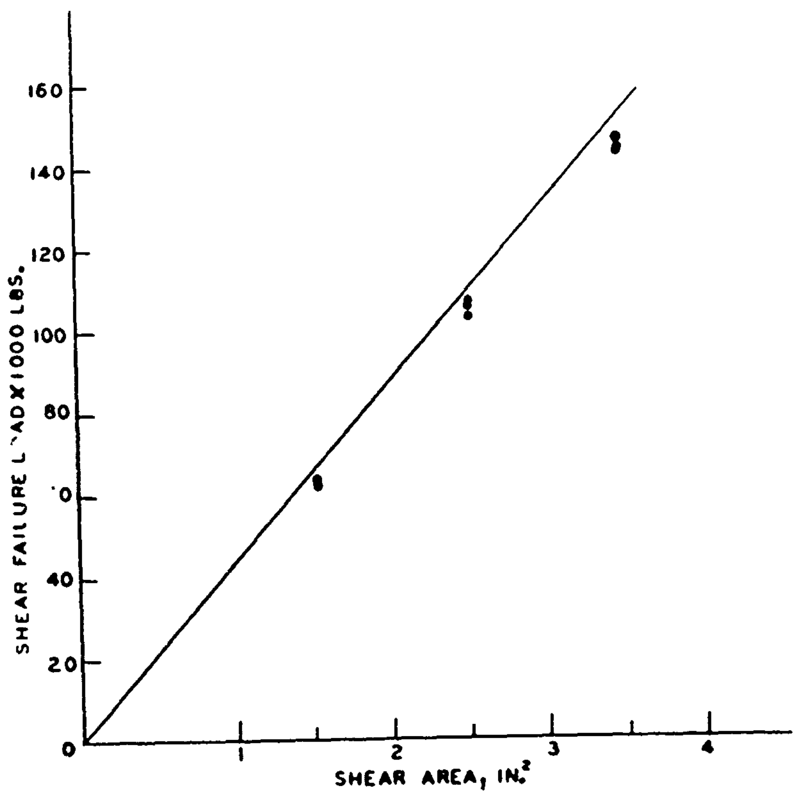
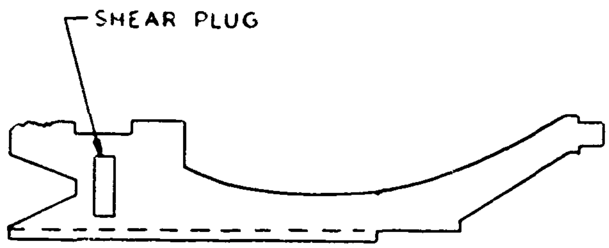


Figure 10. Shear Failure Load Versus Shear Area For Sabot Specimens



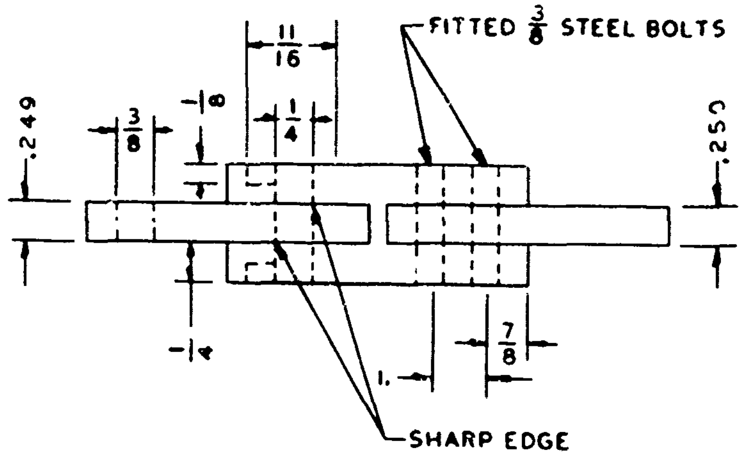


Figure 11 Shear Test Fixture and Orientation and Location of Shear Test Specimen

This is further confirmed by the uniformly rising load deflection curve and a direct fall off to zero load after the peak load has been reached. Further work in this area should be conducted using a uranium penetrator to determine if its material yield strength or elastic modulus changes this result.

SUMMARY AND CONCLUSIONS

A laboratory test apparatus has been developed which can provide a quantitative measure of the structural integrity of a kinetic energy penetrator during launch. The same apparatus can also be used to determine sabot lug integrity during launch. The system is suitable for making material comparisons for both the penetrator and sabot and may be used to determine if different material treatments or service histories have any effect on material and component strength. In addition, the following particular conclusions may be drawn from the testing described above.

1. Based on simulation test failure load, the 90 percent tungsten and uranium penetrators have a similar, high capability of surviving launch while the 97 percent tungsten penetrator is considerably less likely to survive. Based on simulation test plastic deformation, uranium penetrators have much higher capability of surviving launch than tungsten penetrators.

2. The failure stress of 90 percent tungsten penetrators is above the ultimate tensile strength of the material, and the failure stress in notched tension tests of the material is above the ultimate tensile strength. These results indicate that relatively simple notched tension tests can be used to predict the failure of penetrators. Tests in other materials are required to confirm this.

3. The substitution of 7075 T73 for 7075 T6 aluminum alloy, for increased stress corrosion cracking resistance, results in an 11 percent loss in load carrying ability of the sabot lugs. The smaller scatter shown in the T73 results may indicate that the loss in strength in a statistical sense is less than 11 percent; however, further testing is required to verify this.

4. The failure process for the sabot lugs in a series of simulation tests is one in which all lugs fail at once. This was demonstrated by the linear relationship between load to failure and the total shear area of the specimen. This same simultaneous failure would be expected to occur in a launch failure of sabot lugs, at least for the rearmost 11 sabot lugs.

Consideration of the results here along with some prior results can lead to recommendations of critical measures of survivability of penetrator and sabot during launch.

For sabots it is now quite clear that the ultimate shear strength in the short transverse orientation is the most important measure of likelihood for a lug shear failure during launch. The short transverse ultimate shear strength is often about half of the more easily measured longitudinal ultimate tensile strength, but measurements should be made to determine the exact relation between shear and tensile properties for each given material.

For penetrators the situation is not so clear. The comparison of test results in Table IV may help to clarify which test is the best measure of penetrator survivability during service loading. The first listed test result, the average failure stress in launch simulation tests, is certainly a direct measure of survivability; applied stress above this value causes failure. So any test which is proposed as the best measure of survivability must give results consistent with launch simulation failure stress. The difficulty with launch simulation failure stress is that it does not separate uranium from 90 percent tungsten. Ultimate tensile strength can not be relied upon to separate the various materials because it would predict nearly as good properties for the 97 percent tungsten as those for the 90 percent tungsten, and the launch simulation failure stresses do not support this prediction.

TABLE IV. Comparison of Test Results Which Relate to the Survivability of Penetrators

Material	Launch Simulation Failure Stress;		Ultimate Tensile Strength		Plane-Strain Fracture Toughness		Launch Simulation Failure Energy;	
	ksi	(MPa)	ksi	(MPa)	$ksi \cdot in.^{1/2}$	$(MPa \cdot in.^{1/2})$	ft-lb	(Nm)
Uranium - 0.75% Titanium	189	(1303)	210	(1448)	35	(38)	1280	(1741)
Tungsten - 3% Binder	119	(820)	167	(1151)	65	(71)	280	(381)
Tungsten - 10% Binder	189	(1303)	176	(121[illegible]	60	(66)	800	(1088)

The plane-strain fracture toughness results shown in Table IV are a representative value from recent material acceptance tests of uranium and, for the two tungsten materials, the average of five tests each from the same group of penetrators used in launch simulation tests. These results can not be relied upon to properly separate the materials because they also would predict good properties for the 97 percent tungsten, and again, the launch simulation failure stresses do not support this.

The last listed test results in Table IV, launch simulation failure energy, are believed to be the most significant. The lowest failure energy corresponds to the lowest failure stress, and, in addition, failure energy clearly separates the uranium and 90 percent tungsten materials. The failure energies are calculated simply by measuring the area up to failure under the load-deflection curves of Figure 8. Inspection of these curves shows that it is primarily the greater amount of plastic deformation of uranium which increases its failure energy relative to that of 90 percent tungsten. The two materials fail at the same stress in launch simulation tests, so it is the larger plastic deformation of uranium which is believed to increase its survivability during launch.

It is proposed that failure energy in a notched failure test, such as the launch simulation test, is a critical measure of survivability during launch, provided that a fracture toughness controlled fracture does not occur, that is, provided that the fracture toughness is above a critical minimum and defects are smaller than a critical maximum size. To the extent that the loading during target impact is similar in nature to that of the launch simulation test, notched failure energy would also be a critical measure of survivability of a penetrator during target impact. We recommend that notched failure energy be investigated as a proposed critical measure of penetrator survivability for both launch and impact service loading.

ACKNOWLEDGEMENT

We are pleased to credit Mr. J. J. Zalinka for the experimental set-up and testing described in this report. We also wish to thank A. W. Gross for his careful preparation of the sabot models.

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