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UCRL-52057

LONG-ROD PROJECTILES AGAINST OBLIQUE TARGETS: ANALYSIS AND DESIGN RECOMMENDATIONS

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MASTER

April 16, 1976

Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$; Microfiche \$2.25

<u>Page Range</u>	<u>Domestic Price</u>	<u>Page Range</u>	<u>Domestic Price</u>
001-025	\$ 3.50	326-350	10.00
026-050	4.00	351-375	10.50
051-075	4.50	376-400	10.75
076-100	5.00	401-425	11.00
101-125	5.25	426-450	11.75
126-150	5.50	451-475	12.00
151-175	6.00	476-500	12.50
176-200	7.50	501-525	12.75
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Contents

Abstract	1
Introduction	1
Calculations	4
Normal Impact on a Rigid Boundary	4
Calculations at 65° Obliquity	7
Normal Uranium Alloy Rod	7
Hypothetical Uranium Alloy Rod	14
Tungsten Alloy Rod	16
Penetrator Design Considerations	17
Cratering	17
Steady Penetration Process	18
Exit Phase	20
Experimental Studies of Rod Toughness	20
Summary and Recommendations	22
Appendices	26
A. Constitutive and Failure Modeling	26
B. Three-Dimensional Calculations	30

LONG-ROD PROJECTILES AGAINST OBLIQUE TARGETS: ANALYSIS AND DESIGN RECOMMENDATIONS *

Abstract

Computer calculations provide an understanding of impact phenomena associated with long rod penetrators striking targets at oblique angles. The rod and target material behaviors are described by elastic-plastic work-hardening constitutive models. Ductile fracture is simulated by setting all tensile and shear stresses to zero when the calculated plastic deformation reaches a critical value.

The important penetration material properties to defeat a given target are identified. There is no single material property of overriding importance; a combination of properties is required for an efficient penetrator. Experimental results are presented to demonstrate the effects of ductility and toughness on penetration performance. Recommendations for possible improvement are suggested.

Introduction

Long rod penetrators are very effective against armor plate at small angle of obliquity. The high stress levels that occur when a dense material strikes a target at a high velocity can overcome the target strength. The length of the rod determines how long the high stress levels can be maintained against the target. The chief factors responsible for the effectiveness of long rod penetrators in normal impact are density, velocity

and length. For optimum penetrator performance in oblique impact high yield and tensile strengths and toughness become important.

The role of these properties can be understood by examining the sequence of events that occur when a rod strikes a target at an oblique angle. At the instant of impact a very high pressure occurs in the rod and target similar to the shock load in a Hu flyer plate experiment. This pressure

* This work was performed under the auspices of the U.S. Energy Research and Development Administration and funded by the Advanced Research Projects Agency.

is an order of magnitude larger than subsequent pressures that occur after radial rarefactions direct penetrator material away from the line of attack. The high pressure level of the initial impact provides a means for overcoming the target strength and for establishing the flow of material. The rod material properties that contribute to this initial pressure load are high density and very stiff volumetric behavior. In order to maintain the initial pressure for the longest possible time the penetrator-target interface geometries must be such as to minimize the rod free surface around the impact area.

The principal failure mode of the penetrator immediately after oblique impact on a target is jetting of hydrodynamic rod material from the crater area. Penetrator design requirements that minimize the initial jetting are appropriate front end geometry and material properties that permit a conversion of the impact interface from oblique to normal in the shortest possible time. These requirements are important because they initiate target failure. A second mode of rod failure occurs when the lateral load induced by the oblique impact fractures the rod thus reducing the effective length. A material property necessary to minimize this latter failure is toughness. No one material has the optimum combination of

properties that covers the entire sequence of events for oblique impact. The work presented here is directed toward identifying the important rod parameters for the various load conditions that occur during the course of penetration of armor plate targets.

It has been found that long rod penetrators become less effective at attack angles of $\sim 65^\circ$ from the normal and fail completely at larger angles. For a rod hitting a plate at an oblique angle the line-of-sight plate thickness increases with the secant of the attack angle. Examination of the secant function shows that the magnitude increases very rapidly for angles in excess of 65° . At 60° the effective thickness has increased by a factor of two. This result has a major effect on long rod penetrator performance at high angles of obliquity. However, examination of experimental results reveals other mechanisms that also contribute to rod defeat.

Experiments show that rods are deflected if they cannot quickly establish a crater in the target. The failure mechanism is a high velocity jetting of failed material out of the impact zone. The work presented here demonstrates how a successful oblique penetrator must convert the oblique impact interface to a normal one by digging a crater in the target material. The crater

lip that forms provides the mechanism for keeping failed penetrator material directly in front of the rod. The target material property responsible for allowing material to flow up into the lip area material is target toughness. After the lip has formed the target strength actually aids the penetrator by maintaining target material normal to the penetrator.

Since the obliquity is the unique factor in this study the early time behavior of rod-target impact has been emphasized. The geometry considered is a rod striking rolled homogeneous armor steel with an attack angle 65° , impact velocity 1.5 km/s (1.5 mm/ μ s) and no yaw. The rod length-to-diameter ratios are 10:1, the target thickness is one rod diameter. These conditions approximate those for an impact on the first plate of spaced armor.

Calculations were done with rod material properties corresponding to alloys of uranium (3/4 wt% Ti) and tungsten (3% Ni, 1.5% Fe). Failure by fracture was assumed at 26% plastic elongation of the uranium alloy and at 6% for the tungsten alloy. These two materials have similar density,

moduli and flow stress. The important difference is the plastic flow to failure, or toughness. A third calculation was performed assuming a rod of an idealized uranium alloy that could sustain unlimited plastic flow without fracture.

Oblique impact is inherently three dimensional but for these three calculations two-dimensional plane geometry was used. Additional parametric studies were done for normal impact against a rigid boundary in both axisymmetric and planar geometry to study the difference between two and three dimensional impact calculations. In addition, a three dimensional calculation (see Appendix B) of oblique impact between a rod and a rigid boundary was performed. We concluded that the main features of oblique impact can be studied in two dimensional geometry. Zukas¹ of the Ballistic Research Laboratory reached the same conclusion from a detailed computer simulation study of axisymmetric and planar normal impact of projectiles on targets. Those results showed there was a constant scaling factor for the target crater volume for the two geometries.

Calculations

NORMAL IMPACT ON A RIGID BOUNDARY

The first series of calculations were done in simple axisymmetric geometry with the penetrator modeled as elastic perfectly plastic steel with no provision for fracture. The HEMP computer program was used. These calculations were done as a check on the plane strain model and to study the pulsating nature of the loads induced in the rod by the target. This oscillatory phenomenon had been seen earlier by other investigators.²

Figure 1 shows the deformation of the steel projectile 3 μ s after impact with the tip greatly deformed by plastic flow. Figure 2 shows a time plot of the axial stress at a position in the center of the impact area. The initial impact is one-dimensional, and gives a pressure of approximately 20 GPa on the principal Hugoniot of the steel penetrator as expected.

This high stress is subsequently relieved by radial expansion of the free surfaces of the cylinder. The calculated cylinder breathing period of about 1 μ s agrees with the period of Fig. 2. A tensile overshoot can also be seen in Fig. 2.

The initial impact is one-dimensional but after a few transient times of sound signals traversing the diameter of the penetrator the material flow in the penetrator becomes two-dimensional. The largest stress that can be supported now is the flow stress of the penetrator material and it is the flow stress of the penetrator material that decelerates the rod.

The behavior of the early axial stress in the penetrator can be seen in Fig. 3. Each frame of Fig. 3 is a contour plot of the axial stress at a different time. Frame a shows the initial one-dimensional character of the impact at early times. Frame b shows the beginning of a stress relief from the cylinder boundaries.

Fig. 1 Deformation of an elastic, perfectly plastic, steel cylinder 3 μ s after striking a rigid boundary. The yield stress for this calculation is 1.65 GPa.

Fig. 2 Axial stress at the center of the impact region of the steel rod shown in Fig. 1. Negative stress is compression. The tensile stress occurs as the rod expands radially to relieve the impact pressure.

Symbol	Axial stress (GPa)
1	3
2	2
3	1
4	0.1
5	-0.1
6	-2
7	-3
8	-10

Fig. 3 Contours of axial stress for the calculation shown in Fig. 1 at five different times. Tensile regions develop at 0.5 μs .

Fig. 4 Change in volume at the center of the impact region of the steel rod shown in Fig. 1. The dilation between 0.5 and 1 μ s arises from radial expansion to relieve the impact pressure. The residual dilation is from the thermal expansion due to internal heating.

Figure 4 is a time plot of the relative volume at a point on the impact surface on the central line of the penetrator. Contours of relative volume are shown in Fig. 5 at a time of 0.57 μ s and show the extent of the volume dilation at this time. The magnitude of plastic flow at 2 μ s is shown in Fig. 6. The tensile

Symbol	Relative volume (V/V_0)
1	1.03
2	1.02
3	1.01
4	1.005
5	0.995
6	0.990
7	0.998
8	0.996
9	0.994
A	0.992

Fig. 5 Contours of volume change at 0.57 μ s after impact. At this time the center of the impact region is in an expanded state.

Symbol	Equivalent plastic strain (%)
1	1
2	5
3	10
4	20
5	30
6	40
7	50

Fig. 6 Contours of equivalent plastic strain at 2 μ s after impact.

stress seen at the early impact time can cause tensile failure in the nose of the penetrator if the material does not have sufficient toughness. The amplitude of the tensile oscillations depends on the material flow stress. A lower flow stress permits a greater tensile overshoot.

The axisymmetric calculation was repeated in plane strain geometry to check the accuracy of the oblique plane strain model discussed below. The same phenomenology was obtained and it was concluded the oblique plane strain model was appropriate to capture the general oblique phenomenology.

CALCULATIONS AT 65° OBLIQUITY

Three calculations were performed with the HEMP³ computer program using three different penetrator materials. Plane strain geometry was used, i.e.

Fig. 7 Geometry of the oblique angle impact calculations.

plate on plate. The objective was to carry these calculations sufficiently far in time to observe the general phenomenology and identify those properties important to penetrator design. The general dimensions used in the calculations are shown in Fig. 7. Material properties and a detailed description of the constitutive models are given in Appendix A. The 2D calculation is compared with a 3D calculation in Appendix B.

Normal Uranium Alloy Rod

The general phenomenology of oblique impact and penetration using uranium-titanium alloy may be seen in the montage of Fig. 8. Each picture in this series illustrates the start of some new phase of the impact behavior. The most prominent early feature of the oblique impact is the jetting of penetrator material adjacent to the impact area. The jetting becomes more pronounced as the obliquity is increased, and is a major factor in the failure of penetrators at large angles of obliquity. The jet consists of hydrodynamic material trapped between the crater lip and the still unfailed outer edge of the penetrator.

Figure 9 shows the vector field in the penetrator at two different times. It can be seen that the penetrator material is being directed parallel to the surface of the target for those portions of the penetrator

Fig. 8 Computer modeling of the impact of a uranium-alloy (0.75 wt% titanium) on a target of RHA steel inclined at 65° . (a) $3 \mu\text{s}$ after impact. Leading edge (free surface) of penetrator begins to be extruded as a high velocity jet relieving the cratering pressure. (b) $5 \mu\text{s}$ after impact. Rod material is flowing along the target interface. (c) $8.5 \mu\text{s}$ after impact. Crater forms in target. Leading edge of penetrator jet turns away from target. (d) $10.5 \mu\text{s}$ after impact. Back surface of target begins to fracture. (e) $15 \mu\text{s}$ after impact. Crater interface is rapidly steepening. (f) $20 \mu\text{s}$ after impact. Target-penetrator interface has turned normal to the penetrator axis, at a cost of 15% of the rod length. The extruded material will shear off, allowing the rest of the rod to penetrate the target.

that have not actually formed a crater in the target.

Figure 10 is a montage of the pressure oscillations showing isobars at different times. The oscillatory nature of the pressure load is similar to the normal impact results discussed earlier.

Figure 11 is an enlarged view of the impact conditions at $20 \mu\text{s}$. It can be seen that the original oblique

impact has been converted to a normal impact in the sense that the projectile-target interface is now perpendicular to the line of attack. Approximately 15% of the rod length has been expended at this time.

Figure 12 shows the extent of the plastic deformation at $6 \mu\text{s}$ after impact and the current boundary between elastic and plastic regions. Figure 13 illustrates the rotation

Fig. 9 Uranium-alloy velocity field after impact. (a) At 5 μ s, jetting of failed material can be seen along the lower target surface with jet velocity approximately twice the initial penetrator velocity. (b) At 15 μ s, material failure at the front of the penetrator has allowed a large portion of this tip mass to be directed along the surface of the target.

of the armor/projectile interface from oblique towards normal impact as time progresses. In Fig. 14 the growth and contraction of the relative volume can be seen over a period of 15 μ s. This oscillatory behavior is similar to that found previously for the normal impact of a axial-symmetric rod against a fixed boundary. However in this case the expansion is enhanced by the jetting around the target crater (Fig. 4).

The temperature of the material is very high near the penetrator target interface, in fact the internal energy is high enough in some areas to cause local melting. Figure 15 shows the extent of this melting at

6 μ s. The constitutive model removes the shear strength for material that has melted. However, the melted region shown in Fig. 15 had previously failed by ductile fracture and the shear strength had already been reduced to zero. Energy levels are shown at 250 and 190 J/g corresponding to the solidus points at $p = 10$ GPa and at 0 pressure respectively.

These calculations show the importance of enhancing the projectile material properties and the front end design so that the oblique impact is converted to normal as fast as possible. If this isn't done, rod material is lost by the jetting action resulting in a decrease in pressure.

Fig. 10 Pressure distribution and pressure oscillations for the impact of the uranium-alloy penetrator. The tensile strength of this material is about 1.4 GPa.

Fig. 11 Deformation of the uranium penetrator and target 20 μ s after impact. The projectile-target interface has rotated so that the penetrator is approaching normal impact conditions. Approximately 15% of the penetrator length has been expended. This material will shear off from the rod, allowing the remaining length to penetrate the target.

Fig. 12 Plastic deformation in penetrator and target at 6 μ s after impact. (a) Current boundary separating elastic and plastic states. (b) Contours of equivalent plastic strain.

Fig. 13 Profiles of the uranium penetrator and the target at four different times. The solid lines along the length of the penetrator divide the upward from the downward flow fields. The dash line defines the limits of hydrodynamic material. Note the rotation of the interface toward normal impact configuration.

Fig. 14 Profiles of the uranium penetrator and the steel target at different times showing the volumetric oscillations in the uranium penetrator. The sequence shows the regions of the penetrator that are in compression (shaded) and in expansion as a function of time. At 5 μ s an expansion wave begins and increases until about 10 μ s. After that the oncoming rod material recompresses the expanded portion at the impact end. The recompression is completed at about 15 μ s. The dilation close to the interface is due to thermal heating.

Fig. 15 Profile of the uranium penetrator and the target at 6 μ s after impact. The contours outline regions that have melted. The dashed contour contains material which would be melted at $p = 0$. The solid contour contains material which would be melted if $p = 10$ GPa.

Also, the initial shock pressures before jetting are perhaps two orders of magnitude higher than the later pressure after full contact has been established. Maintaining this initial pressure for the longest possible time imposes a requirement that the impact area of the nose of the projectile be as large as possible so that it takes the longest time for signals from the release surface to reach the impact area and reduce the pressure.

Hypothetical Uranium Alloy Rod

The constitutive model of uranium used in the previous calculations was modified to permit unlimited plastic flow without ductile fracture. This would represent a hypothetical material similar to uranium alloy but with essentially infinite toughness. Figure 16 shows a comparison of the

Fig. 16 Comparison of calculated crater formation using hypothetical uranium alloy and normal uranium alloy penetrators at 5 μ s after impact. The hypothetical uranium alloy is capable of infinite elongation without failure. All its other properties are the same as those of the normal uranium alloy (0.75 wt% Ti).

results of this hypothetical material with the results of the normal uranium at 5 μ s after impact. The crater created by the idealized material is considerably greater than that created by the normal uranium rod where the deformation to failure is defined to be 26%. The ability to resist shear deformation and not incur ductile fracture is a very important property for the success of the penetrator. The magnitude of the shear strength of the penetrator strongly influences the pressure load that the penetrator can place on the target after full contact has been established. Penetration efficiency requires maintaining the greatest possible load for the longest time on the target.

Figure 17 shows pressure contours

in the target and penetrator for the calculations with the hypothetical uranium alloy and the normal uranium alloy. The hypothetical uranium alloy has induced much larger pressures into the target. This increased pressure load turns the target impact surface normal to the penetrator much more quickly. The kinetic energy of the penetrator can now act over a longer period of time at nearly normal incidence.

In the constitutive model used to describe the material behavior of the target and penetrator, materials yield first by plastic flow after the elastic limit has been exceeded. For subsequent loading of the material the shear strength or resistance to plastic flow increases by work hardening. When the critical equivalent

Fig. 17 Comparison of pressure states using hypothetical uranium alloy and normal uranium alloy penetrators at 2 μ s after impact. The hypothetical uranium is capable of infinite elongation without failure. All its other properties are the same as those of the normal uranium alloy (0.75 wt% Ti).

plastic strain^{*} has been reached the material is assumed to fail catastrophically by ductile fracture and only compressive pressures can be supported. The modified uranium alloy examined the effect of the equivalent plastic strain parameter. With the failure condition removed, the penetrator has been assumed to possess shear strength with infinite ductility. It is certainly obvious that a higher penetration shear strength would increase the pressure load on the target. In order for this pressure load to persist the penetrator shear strength must continue to exist for large deformations. Unfortunately, materials with high shear strengths are usually accompanied by poor elongation-to-fracture properties.

At first it might be thought that it would be very beneficial to have a material with unlimited ductility to gain the advantages seen in the results in Fig. 16 and 17. Even if it were available, however, this property would be useful only at the time of impact for quickly forming a crater in the target. As time progresses

^{*}Equivalent plastic strain

$$\epsilon^P = \frac{\sqrt{2}}{3} \sqrt{(\epsilon_1^P - \epsilon_2^P)^2 + (\epsilon_2^P - \epsilon_3^P)^2 + (\epsilon_3^P - \epsilon_1^P)^2}$$

where ϵ_1^P , ϵ_2^P , and ϵ_3^P are principal components of the plastic strain. This is a measure of the total plastic deformation which reduces to ϵ_1^P in uniaxial tension.

the penetrator is continuously deformed. This deformation increases the cross section of the penetrator making it less effective against subsequent targets in spaced armor geometries. Thus the inability of the penetrator to fail ductily actually tends to degrade its performance after the crater has been formed.

Tungsten Alloy Rod

The tungsten-nickel-iron alloy is similar in density to the uranium. The material is slightly stiffer than uranium with resulting sound speed approximately 60% greater than uranium. However, the main difference between the two materials is that the plastic deformation to fracture of the tungsten-nickel-alloy is 6% vs 26% for the uranium alloy.

Figure 18 compares results for the tungsten alloy material with the uranium alloy 10 μ s after impact. It can be seen that the interface between the projectile and target has not rotated as far for the tungsten alloy as for the uranium penetrator. This result follows from tungsten's failure at a smaller plastic elongation than the uranium. Thus the uranium is able to maintain a larger stress on the interface compared to the tungsten. Also, because of the longer period of obliquity the tungsten rod loses more material during this initial phase of the penetration.

Fig. 18 Comparison of the uranium- and tungsten-alloy penetrators at $10 \mu s$ after impact. The projectile-target interface has rotated more toward the normal for the uranium alloy than for the tungsten. More of the tungsten than of the uranium has been deflected, indicating that a larger region of the tungsten penetrator has failed. The deformation of the target is more localized for the case of the uranium penetrator.

Penetrator Design Considerations

The calculations and supporting experiments have identified three general penetration stages:

- Initial cratering and conversion from oblique geometry to normal impact geometry by rotation of the target projectile interface.
- Steady penetration as the rod erodes and moves into the target plate under conditions similar (but not identical) to normal impact.
- Passage of the eroded and deformed rod through the hole in the armor plate.

Different portions of the penetrator undergo different load environments during these three phases. An effective penetrator design should recognize these load differences. A cylindrical high strength rod is not necessarily an optimal design for a long rod penetrator.

CRATERING

It is important in oblique impact to establish a target crater as soon as possible. To do this a high impact pressure must be created and maintained. Material properties that create high impact pressures are high density

and large bulk and shear moduli contributing to a high shock impedance.

The theoretical impact pressures for tungsten and uranium impacting on iron can be seen in Fig. 19. It is seen that tungsten yields a slightly higher impact pressure for the impact velocity considered here of 1.5 km/s. However it is important that the impact pressure be maintained. This places a requirement for ductility or toughness, indicating a possible tradeoff between toughness and impact pressure.

Another factor that extends the pressure pulse is the geometry of the impacting surface. It is important to have the largest cross section possible impact the target; this delays the jetting and allows the

Fig. 19 Shock Hugoniot curves for uranium and tungsten alloys striking armor plate in one-dimensional geometry. Tungsten produces a somewhat higher impact pressure than uranium.

pressure to be maintained for the maximum time. This suggests using a hemispherical head with the largest possible diameter. The large impact area of such a design places the free boundaries as far as possible from the impact point to delay as long as possible the release of pressure by lateral rarefactions.

The impacting head of the projectile must also be able to withstand the tensile phases of the initial oscillations. As was pointed out earlier, we can reduce the amplitude of the oscillations by increasing the yield strength of the material. For ordinary materials, however, increasing the yield strength decreases the ductility and the toughness. Hence there is another tradeoff between the magnitude of the flow stress and the ductility and toughness.

STEADY PENETRATION PROCESS

Following the establishment of the crater and conversion of the oblique impact to one of normal incidence, the normal impact calculations (see Fig. 2) suggest a convergence of the stress oscillations to a steady penetration process, with target pressure somewhat higher than the penetrator yield strength. The rod moves into the target at about half of the initial penetrator velocity. The stress at the rod elastic-plastic interface is the yield stress of the penetrator material. This flow stress maintains

the lower bound pressure on the target and acts to decelerate the aft section of the penetrator. This aspect of the penetration process is essentially independent of the impact angle.

If the impact angle is oblique, however, angular momenta left over from the cratering phase continue to exert large lateral loads. The

results of these lateral loads have been seen in experiments performed here and at the Los Alamos Scientific Laboratory. Hantel and Taylor^{4,5} have been able to follow the steady penetration process through thick targets with low-aspect-ratio penetrators at 45° obliquity. Their results (see Fig. 20) show rotation away from the normal during the early

Fig. 20 Radiographs of penetrator passage through a thick target, from Hantel and Taylor^{4,5}. (a) 50 μ s, unwayed impact with typical jet flow of failed material. (b) 100 μ s, rotation away from the normal due to relief of the upper target surface. (c) 150 μ s, continued rotation away from normal (inertia). (d) 200 μ s, rotation toward the normal as the closest free surface (rear) begins to give way. The rarefaction wave reduces the target retarding force below the penetrator.

penetration and back toward the normal as the penetration approaches the exit phase. It is important to give the penetrator enough toughness to prevent it from breaking under these large bending stresses.

EXIT PHASE

As the rod exits the first plate it is important that it still have about the same shape it had before the original impact. Appreciable distortion will limit its ability to

penetrate subsequent shields. This means that the penetrator must be able to shed the material that was expended in forming the original crater, and that this gross distortion not be transmitted any farther back into the rod than necessary. The toughness provided to prevent fracture by the bending moments of the penetration phase must not be large enough to prevent this beneficial sloughing off of expended material.

Experimental Studies of Rod Toughness

Tool steel rods were fabricated with various Rockwell hardnesses and fired at mild steel plate. Figure 21 shows a flash radiograph of a rod with a hardness of 40 on the Rockwell C scale ($R_C = 40$) after it has penetrated a plate. The high ductility of this material has allowed a large deformation to take place. For subsequent plates the rod would not be effective since it would present a very large cross sectional area to a secondary target.

Figure 22 shows the result with a rod that has been hardened to $R_C = 62$. The rod has fractured since this hardness makes it more brittle than the rod described previously. The fractured rod would also be ineffective against subsequent targets.

Figure 23 shows the results for a rod that has been hardened to $R_C = 48$. This rod has penetrated the target, has not fractured, and has maintained its original shape. It is understood of course that as the hardness increases the toughness decreases. These three experiments show the tradeoff between hardness and toughness. Further details are given by Scudder.⁶

These experiments suggested a design with a forward section of very high hardness and the material behind of a lower hardness. The concept here is that the high hardness of the front would induce a large stress into the target and the forward zone would fail by brittle fracture thus not transmit the deformation into the

Fig. 21 Flash radiograph of a steel penetrator impacting a steel target at 45° obliquity. The steel penetrator has been heat treated to a hardness of 40 on the Rockwell C scale (R_C-40). The radiograph shows the large distortion in the projectile after it has penetrated the target due to high ductility.

Fig. 22 Flash radiograph of a steel penetrator heat treated to R_C-62 , showing the fragments of the penetrator emerging from the rear of the target.

Fig. 23 Flash radiograph of a steel penetrator heat treated to R_C-48 . The rod has successfully penetrated the target, is still lined up on the original flight path, and is bent but has not fractured.

rod. The subsequent portions of the rod would have less hardness or flow strength but would have sufficient toughness to withstand the lateral loads.

A rod similar to this design was made with steel. Figure 24 shows a schematic of the variation of hardness

along the rod length. When tested against oblique targets that defeated all three of the previous rods the rod with the variable hardness penetrated the target and was sufficiently aligned to make it a threat for subsequent targets. The same rod showed no improvement at normal incidence.

Fig. 24 Variation of hardness along an experimental steel rod penetrator, Rc-62 at the impact end. Varying the hardness made this penetrator better able to withstand the different loads imposed during different phases of the penetration process. It outperformed all the uniform homogeneous steel rods tested.

Summary and Recommendations

It might seem from these studies that there are contradictory requirements for material behavior of long rod penetrators. The fact that there is more than one loading mechanism acting on rod penetrators leads to different requirements for material properties. Two rods fabricated from different materials can give similar penetration results, but not for all of the same reasons. For example, a rod with a high toughness* at the tip is efficient in forming the initial crater in a target, thus minimizing the loss of rod material by jetting. However, after the crater has formed the high toughness tends to work against the rod performance for subsequent targets. The large plastic

distortions introduced into the rod moves material off center and makes it easier for a second armor plate to defeat the rod.

Long rod penetrators of tungsten alloy and uranium alloy provide the means to study variations in toughness. The tungsten alloy has an advantage over the uranium alloy because of the higher shock impedance which causes a high stress level at the projectile target interface. This advantage is offset by the lower tungsten toughness (in the model used here) which does not permit the high stress level to be sustained. Fracture occurs and rarefactions reduce the stress. On the other hand the initial impact stress is lower for the uranium alloy but the duration is longer due to the higher toughness. This advantage is later offset by the distortion of a large portion of the rod making it less effective for subsequent targets. Thus it is

*Toughness measures the product of the flow stress and the elongation to failure. For the rod/target phenomena described here it is important to have a high flow stress with sufficient elongation to failure so that the flow stress is maintained over the times of interest.

seen that both materials can make efficient penetrators, but for different reasons.

It has been shown that there is a minimum requirement for toughness such that bending stresses do not fracture the rod at positions well behind the front as occurred in the experiment with a high hardness, R_C - 62 steel rod experiment discussed earlier. For resistance to fracture by bending, the uranium alloy is much superior to the tungsten alloy; the large range of plastic flow in uranium (see Fig. 25) prevents large tensile stresses from developing.

The computer studies have helped identify different mechanisms and different material requirements for optimum penetrator designs. The calculations provide guidance for designing a rod with different material properties along the rod. This could be accomplished with a given material by trading off one material property at the expense of another.

It is recommended that rods with varying properties be designed and tested at small scale similar to the experiments with steel reported here. These experiments were conducted at 1/10 the actual size of current long rod penetrators. Considering the tungsten alloy it would be interesting to introduce maximum ductility into the rod starting a few rod dia-

Fig. 25. Strain-hardening characteristics of materials used in armor-penetrator calculations.

meters behind the impact end. The spacial variation in material properties might be accomplished by powder metallurgy techniques with appropriate swaging.

The uranium alloy may have more elongation to fracture than is necessary for the armor considered here. It would be very instructive to test an uranium alloy that has a higher critical flow stress even at the expense of less elongation to failure. The objective here is to enhance the initial load on the target so that the crater forms sooner.

The modified uranium calculations have demonstrated the effectiveness of maintaining the flow strength through a high toughness criterion to enhance crater formation. As a practical matter it is probably impossible to get sufficient fracture toughness to capitalize on this property but the idea has merit and should be investigated experimentally. Some

easy tests would check crater size for very ductile alloys vs nonductile alloys. Small sphere tests could easily examine the initial cratering phenomenon and assess the relevance of the concept.

Finally, geometric design should be tried such as a uranium alloy tip followed by a tungsten alloy that has been modified to resist fracture from bending stresses. The objective is to use the large elongation to failure of the uranium to form the initial crater. Decoupling the uranium from the tungsten would provide the means to prevent large deformations from occurring in the remaining portion of the rod.

In summary, the calculations and supporting experiments show the optimum design for a cylindrical penetrator would recognize the three stages of oblique penetration and the associated penetrator loads: cratering, steady penetration, and exit as the rod moves through the opened hole. The material properties and geometry which are important are

Head design - cylindrical head with highest density and

moduli. Maximum toughness is required to keep the head together during crater formation. Practical limitations on toughness and a short section preclude excessive effective lateral expansion.

Forward section - maximum flow stress (ultimate stress) with adequate ductility to reduce fracture.

Aft section - bending loads here are more severe and ductility and toughness play the major role.

It should be understood the material models used for these calculations are not meant to define precisely the behavior of Tungsten or Uranium. We feel the models are representative of alloys of specific metallurgical treatment. The emphasis should be on how the material properties described by the models enhance (or reduce) the effectiveness of a penetrator against oblique targets.

REFERENCES

1. J. Zukas, Ballistic Research Laboratory, private communication (1976).
2. C. H. Karnes and L. D. Bertholf, "Numerical Investigation of Two-dimensional, Axisymmetric Elastic Plastic Wave Propagation Near the Impact End of Identical 1100- $\frac{1}{2}$ Aluminum Bars," in *Inelastic Behavior of Solids* (McGraw Hill, New York, 1970), pp 501-519.
3. M. L. Wilkins, *Calculations of Elastic-Plastic Flow*, Lawrence Livermore Laboratory, Rept. UCRL-7322, Rev. 1 (1969).
4. L. W. Hantel and J. W. Taylor, *PHERMEX Evaluation of Air Force Tungsten and U-0.75 wt% Ti Penetrators*, Los Alamos Scientific Laboratory, Albuquerque, NM, Rept. LA-5658 (1974) (title U, report CRD).
5. L. W. Hantel and J. W. Taylor, *PHERMEX Evaluation of Air Force Designed U-0.75 wt% Ti Penetrators*, Los Alamos Scientific Laboratory, Albuquerque, NM, Rept. LA-5817 (1975) (title U, report CRD).
6. J. K. Scudder, *Report on Oblique Impact Armor Penetration Studies, Part 1*, Lawrence Livermore Laboratory, Rept. UCRL-52020 Pt. 1 (1976) (title U, report CRD).

Appendix A

CONSTITUTIVE AND FAILURE MODELING

Since the behavior of the penetrator is dependent upon the dynamic stress fields set up by the impact, a great deal of care has gone into the constitutive modeling and the choice of material parameters for these calculations. The equation of state constants have been matched to experimental Hugoniot data^{A1} over the range of pressure and compressions which will be met during the impact. The strain hardening in the constitutive equations is described by the Steinberg-Guinan^{A2} model which gives the dependence of the shear modulus and yield strength of a material as a function of the equivalent plastic strain ϵ , compression, pressure and internal energy through the equations:

$$G = G_0 F(P, \eta, E) \quad \text{shear modulus}$$

$$Y = Y_0 (1 + \beta \epsilon)^n F(P, \eta, E) \quad \text{yield strength}$$

$$\text{where } F(P, \eta, E) = \left\{ 1 + b \frac{P}{\eta^{1/3}} + h \left[\frac{E - E_c}{3R'} - 300 \right] \right\} \exp \frac{-fE}{E_m - E}$$

G_0 = reference state shear modulus

Y_0 = reference state yield strength

P = pressure

ρ = density

η = ρ/ρ_0 , the compression

E = internal energy

E_c = cold compression energy

E_m = melt energy as a function of pressure

$R' = R\rho_0/\Lambda$ with R = gas constant and Λ = atomic number

$$\epsilon = \sqrt{2/3} [(\epsilon_1^p - \epsilon_2^p)^2 + (\epsilon_2^p - \epsilon_3^p)^2 + (\epsilon_3^p - \epsilon_1^p)^2]^{1/2}, \quad = \text{equivalent plastic strain}$$

where $\epsilon_1^p, \epsilon_2^p, \epsilon_3^p$ = principal components of the plastic strain and other constants: β, n, b, h, f are fitting constants used to match the dependence with experimental data. The dependence of the yield stresses as a function

of the effective plastic strain described by the parameters $\dot{\epsilon}$ and n has been matched as well as possible to experimental data.^{A3-15} The resulting dependence was illustrated in Fig. 25 for the materials of the calculations. The specific parameters used for each material are itemized in Table A1.

Table A1. Specific material parameters used in constitutive and failure modeling of penetrator impacted.

Parameter	Uranium	Tungsten	Armor
G_0 (GPa)	76.6	1.375	0.776
Y_0 (GPa)	0.987	0.0138	0.01034
$\dot{\epsilon}$	40	0	7.37
η	0.16	1.0	0.115
c^p	0.26	0.06	0.20
$P_{\min}$ (GPa)	-0.4	-0.6	-0.4

The failure of the material by ductile fracture was modeled by defining a critical equivalent plastic strain, $\epsilon_{\max}$. Once this value was exceeded the shear modulus and yield strength were relaxed to zero over a few computational cycles and the subsequent behavior of the material was hydrodynamic where only compressive stresses were allowed to develop.

REFERENCES

- A1. R. C. Schroeder and W. H. McMaster, *Compilation of Shock Hugoniot Data and Hugoniot Melting Points for the Elements*, Lawrence Livermore Laboratory, Rept. UCRL-51253 (1972).
- A2. D. J. Steinberg and M. W. Guinan, *Constitutive Relations for the KOSPALL Code*, Lawrence Livermore Laboratory, Rept. UCID-16226 (1973).
- A3. A. M. Ammons, *Precipitation Hardening in Uranium-Rich Uranium-Titanium Alloys*, Union Carbide, Oak Ridge, TN, Rept. Y-DA-5353 (1973).
- A4. D. A. Colling, *Uranium Alloys for XM-873 Projectile*, Army Materials and Mechanics Research Center, Watertown, Mass., Rept. AMMRC SP 72-17 (1972).
- A5. E. A. Green, Lawrence Livermore Laboratory, Internal Document ENS 68-314 (1968). Readers outside the Laboratory who desire further information on LLL internal documents should address their inquiries to the Technical Information Department, Lawrence Livermore Laboratory, Livermore, California 94550.
- A6. G. Simmons and H. Wang, *Single Crystal Elastic Constants and Calculated Aggregate Properties, A Handbook* (MIT Press, 1971).
- A7. D. H. Wood, Lawrence Livermore Laboratory, private communication (Chemistry Department Technical Note #73-21) (1973).
- A8. P. N. Brooks, *An Experimental Study of the Tungsten Alloy Kennertium W-2 as a Penetrator Material*, Defense Research Establishment, Valcartier, Rept. DREV TN-1995/72 (1972).
- A9. W. G. Northcutt, *Fabrication of Tungsten Alloy Penetrators*, Oak Ridge Y-12, TN, Y-1994 (1975).
- A10. M. L. Wilkins and M. W. Guinan, *J. Appl. Phys.* **44**, 1200 (1973).
- A11. L. W. Hantel and J. W. Taylor, *PHERMEX Evaluation of Air Force Designed U-0.75 wt% Ti Penetrators*, Los Alamos Scientific Laboratory, Albuquerque, Rept. LA-5817 (1975).
- A12. B. R. Queneau, "Iron and Steel", and C. W. MacGregor, "Mechanical Properties of Materials", in *Standard Handbook for Mechanical Engineers*, T. Bauneister, Ed. (McGraw Hill, 1967).
- A13. K. A. Gschneidner, "Physical Properties and Interrelationship of Metallic and Semimetallic Elements", *Solid State Physics*, F. Seitz and D. Turnbull, Eds. (Academic Press, 1964) vol. 16, p. 275.

- A14. R. W. Rhode, *J. Appl. Phys.* 40 (7), 2988 (1969).
- A15. J. Wolf, Ed., *Aerospace Structural Metals Handbook*, Mechanical Properties Data Center, Belfour-Stulen, Inc., Rept. AFML-TR-68-115 (1972).

Appendix B

THREE-DIMENSIONAL CALCULATIONS

In order to compare a three-dimensional cylindrical calculation with a two-dimensional plane strain calculation we performed calculations for an impact on a rigid wall at 65° obliquity. An impact velocity of 0.5 km/s was chosen to produce impulse pressures similar to those of the penetration calculations. The results for both calculations appear in Fig. B1. Both show the projectile being bent and subsequently sliding along the rigid wall. The general phenomenology was found to be similar although there were some differences in detail attributable to different models in the programs.

Fig. B1 Comparison of two- and three-dimensional calculations of a penetrator striking a rigid boundary at 65° obliquity. Top: at impact. Bottom: $24 \mu\text{s}$ after impact.