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COMPARATIVE EFFECTIVENESS OF ARMOR-DEFEATING AMMUNITION

Paper Presented at Symposium on
Shaped Charges
Ballistics Research Laboratories
Aberdeen Proving Ground
Maryland
13-16 November 1951

By

A. Hurlich
Metallurgist

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Comparative Effectiveness of Armor-Defeating Ammunition

There are, at present, two major types of armor-defeating ammunition; projectiles which depend upon their own kinetic energy to pierce or punch a hole through armor, and explosive-loaded shell which, upon impact and detonation against armor, generate the energy required for the defeat of the target.

The kinetic energy projectiles consist of more or less massive, cylindrical, ogival-nosed inert shot made of hardened steel or tungsten carbide compacts designed to have sufficient strength to remain substantially intact during the penetration cycle. The armor penetration characteristics of such projectiles depend largely upon their mass and velocity, consequently best armor penetration performance results when they are fired from high velocity guns. Kinetic energy projectiles may be further subdivided into a number of types; monobloc (AP) and capped (APC) steel shot, also composite-rigid (HVAP) and discarding sabot (HVAPDS) tungsten carbide cored shot. Monobloc steel shot are the most simple in design and least expensive of all types, consisting of a solid steel body to whose nose a windshield, made of a thin steel stamping, may be attached to improve its exterior ballistic performance. The steel bodies of AP and APC shot are made of alloy steel differentially heat treated so that the nose sections have maximum strength and hardness, with the hardness gradually decreasing towards the bases to provide tough fracture-resistant body sections. The APC shot differ from the AP shot only in the possession of a steel cap placed over the nose of the shot for the purpose of cushioning the forces on the nose of the shot resulting upon impact against armor. The cap thus assists in keeping the point of the projectile intact.

HVAP shot contain sub-caliber sized tungsten carbide cores fixed within light-weight metallic carriers of gun bore diameter. The carrier accompanies the core to the target, at which point the core breaks out of the carrier to effect the penetration. By virtue of its high density and high strength, tungsten carbide is a more effective penetrator than steel. In addition, because of the combination of a light-weight carrier and a sub-caliber core, the HVAP shot weighs less than a full caliber steel shot and thus achieves a higher muzzle velocity when fired from the same gun. Since the energy required to effect penetration is approximately proportional to the volume of the hole produced in the armor, the greater armor penetration performance of the HVAP projectile is, under ideal conditions, obvious.

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Because of the lighter weight and consequent lower sectional density of the HVAP shot, this type of projectile has poorer range-velocity characteristics than steel shot. Although it may have a muzzle velocity initially 500 to 700 ft/sec higher than an AP shot, the HVAP shot will have dissipated most of this advantage within 2000 yards' range. In order to overcome this deficiency, the HVAPDS shot was developed. The tungsten carbide core is carried within a thin steel sheath and supported, during firing, in a metallic or plastic carrier which is discarded shortly after the projectile emerges from the muzzle of the gun. The sub-projectile of high sectional density proceeds to the target unencumbered by any useless mass.

The explosive loaded or chemical energy armor-defeating ammunition consist of the high explosive plastic (HEP) shell and the hollow charge (HEAT) shell. The HEP round has a thin, hemispherical, deformable ogive and a base detonating fuze. Upon impact, the forward portion of the shell collapses against the target and, upon detonation, a compressive shock wave parrallel to the plate surfaces travels through the armor, is reflected as tensile waves, and produces a fracture parrallel to the plate surfaces. A disc, having a thickness of approximately 25-30% of the plate thickness, is detached from the back of the armor at velocities of 500-1000 ft/sec and, within the narrow confines of the interior of a tank, may produce considerable damage. The HEP shell rarely perforates armor in the true sense of the word, unless the armor is quite brittle, but inflicts damage by a combination of disc formation and shock. The force of the detonation of HEP shell may produce considerable damage of a secondary nature through disruption of tank treads, detachment of fittings, etc.

The hollow charge round produces a high velocity jet of discrete particles which perforate armor by forcing aside the plate material which is in the path of the jet. The metal surrounding the hole is compressed by this action. The HEAT ammunition is too well known by this audience to justify any further discussion of its functioning.

I will first describe the armor penetration performance of kinetic energy and chemical energy projectiles against simple targets and then discuss their performance against more complex targets.

Performance of Kinetic Energy Projectiles Against Simple Armor Targets

I shall not attempt to present any equations to describe the armor penetration performance of kinetic energy projectiles; firstly because all equations which have been proposed in the past are found to apply, with a good degree of accuracy, to only a limited range of target conditions, and secondly, because a large number of geometrical, metallurgical, and mechanical property variables existing both in present service projectile and armor exert a profound influence upon the mechanisms of armor penetration and projectile reaction.* Variables such as plate hardness may be introduced into penetration formulae, but factors such as variations in projectile nose shape, microstructure, toughness, and soundness of the projectile and armor steels cannot be readily reduced to mathematical terms.

An important consideration in the penetration of armor by kinetic energy projectiles is the ratio of armor thickness to projectile diameter (the e/d ratio) since the mechanisms of armor penetration and projectile behavior vary with the e/d ratio. When the e/d ratio is greater than 1 (armor overmatches the projectile), the penetration tends to be effected by a ductile pushing-aside mechanism. Relatively sharp nosed shot are most effective, and the resistance of the armor generally increases as its hardness increases. When the e/d ratio is less than 1 (armor undermatches the projectile), the penetration tends to be effected by the punching or shearing out of a plug of armor in front of the shot. Relatively blunt nosed shot are most effective under this condition of attack, and the resistance of the armor generally increases as its hardness decreases.

Data on the comparative armor penetration performance of kinetic energy projectiles of the AP, APC, and HVAP types are included in Table I. This table compares the penetration performance of the 90MM AP T33, the 90MM APC T50, and the 90MM HVAP M304 shot when fired at cast and rolled homogeneous and face-hardened armor from 3" to 7.6" in thickness at obliquities of 30° to 70°. The comparative performance of these kinetic energy projectiles against solid armor targets may be summarized as follows:

a. Monobloc steel shot are more effective than capped steel shot for the defeat of undermatching armor at all obliquities of attack and are more effective than both APC and HVAP shot for the defeat of moderately overmatching armor (up to at least 1-1/4 calibers thick) at all obliquities of attack above approximately 45°.

b. Capped steel shot are superior to monobloc steel shot for the defeat of greatly overmatching armor, (over 1-1/4 calibers in thickness) at obliquities in the range of 20° - 45°, but both capped and monobloc shot are greatly inferior to HVAP shot in the low obliquity range against heavy armor targets.

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* This is not to imply that the factors which influence penetration are unknown, that the performance of kinetic energy projectiles is very variable, or that penetration data are either scanty or unreliable. As a matter of fact, it is because penetration data are so reliable and so extensive that we are not satisfied with equations that yield only approximately correct estimates.

c. HVAP and HVAPDS shot are most effective against heavy armor targets at low and moderate obliquities of attack (the 90MM tungsten caribde cored shot can penetrate 10 to 12 inches at 0° obliquity and at short ranges) but their effectiveness is markedly degraded at obliquities above approximately 45°-50°.

The preceding statements regarding the comparative performance of AP and APC shot are well illustrated by Figures 1 and 2. Figure 1 represents data obtained from terminal ballistic tests conducted at the Watertown Arsenal Laboratory in which caliber .40" scale models of the 90MM AP T33 and 90MM APC T50 shot were fired at plates from 1/2 to 2 calibers in thickness and at obliquities from 0° to 70° inclusive. The curves on Figure 1 represent equal resistance curves; i.e. all plate thicknesses and obliquities whose coordinates fall on the line designated 3000 have ballistic limits of 3000 f/s. The lines furthermore represent the minimum ballistic limit for the target conditions, whether the minimum ballistic limit was obtained with AP or APC projectiles. The dashed line represents the boundary between target conditions where the AP shot was superior and where the APC shot was superior. It will be noted that the areas of superiority of the AP over the APC shot and vice versa are in accord with the previous conclusions.

The data plotted in Figure 1 represent very precisely determined ballistic limits obtained over a wide range of target conditions. Similar data in full scale would involve the expenditure of several million dollars, hundreds of tons of steel armor and thousands of rounds of 90MM armor-piercing projectiles.

Figure 2 represents a similar treatment of data obtained in full scale tests conducted at Aberdeen Proving Ground. These data are necessarily more limited in scope than those used to obtain the curves shown in Figure 1 and hence the boundary conditions of Figure 2 are considerably less reliable than those shown in Figure 1. The same general type of curve results, however.

A useful way of presenting penetration data on kinetic energy projectiles is by means of vulnerability diagrams of the type shown in Figure 3. A roughly elliptical area exists for each gun-projectile-armor combination within which penetration of the armor can be effected and beyond which the armor is invulnerable to the particular attack. The gun must enter into this consideration since it influences the velocity and hence the kinetic energy of the shot at all ranges.

Figures 4 and 5 show the use of vulnerability diagrams to illustrate the comparative performance of AP and APC projectiles against various thicknesses of armor sloped at different obliquities. It will be noted that, for a fixed weight of armor per unit vertical height, thinner plates sloped at higher obliquities (at least up to 53°) provide progressively more protection against APC shot. Against AP shot, however, a given weight of armor sloped at 37° obliquity provided considerably more protection than the same weight of armor in the form of a thinner plate sloped at 53° obliquity. A comparison between the righthand curves of Figures 4 and 5 illustrates the improved effectiveness of AP shot in attacking highly sloped armor targets.

Figure 6 illustrates the weights of steel armor required to protect against kinetic energy projectiles at ranges of 1000, 2000, and 3000 yards as functions of the obliquity of disposition of the armor and the caliber and type of armor-piercing projectile. Note the steep downward slope indicating the marked degradation in performance of HVAP projectiles with increasing obliquity of attack. It is also apparent that protection against APC shot increases constantly as the obliquity increases, whereas armor is most effective against AP shot at about 30° obliquity, then becomes progressively more vulnerable with increasing obliquity above 30°.

Early in World War II, kinetic energy projectiles were fired from guns with muzzle velocities of 2000-2700 ft/sec. By the end of World War II, steel shot were being fired at velocities up to 3200 f/s and present guns are being built to fire solid steel shot at velocities up to 3500 f/s and HVAP and HVAPDS shot at velocities of 4000-4500 f/s. Coupled with these high velocities are good stability, high accuracy, and high rate of fire. These factors combine to yield a high probability of registering a damaging hit with kinetic energy shot. It is firmly believed that kinetic energy shot will, at least in the foreseeable future, play an important role in tank and anti-tank warfare.

Performance of Chemical Energy Projectiles
Against Simple Armor Targets

The available data on the armor-defeating performance of high explosive plastic (HEP) shell indicates that this round can cause the scabbing or spalling of armor up to 1.3 calibers in thickness over a wide range of obliquities. Unlike kinetic energy armor-piercing projectiles, the performance of HEP shell is not greatly influenced by obliquity of attack at least within the range of 30° to 60°; the same thickness of armor can be defeated over this whole range of obliquities. As a matter of fact, the performance of HEP shell is worse in the range of 0° to 30° obliquity than at higher obliquities due primarily to the fact that the explosive charge is not spread over the face of the armor as effectively at very low obliquities as it is at higher obliquities. The HEP shell is also degraded at obliquities of attack above approximately 60°.

HEP shell perform satisfactorily at striking velocities up to approximately 2500 f/s, but at higher impact velocities this shell is relatively ineffective because of shock detonation of the explosive which initiates at the nose of the shell at these high velocities. To perform satisfactorily, detonation must be initiated at the base of the shell to permit the generation and travel of a shock wave from the explosive to the target.

It has been determined that brittle steel armor and unsound steel containing laminations or segregations of inclusions are more readily defeated by HEP shell than are tough, sound steels. There is reason to believe that HEP shell become increasingly effective in cold climates since the toughness of steel armor decreases with decreasing temperature, particularly if the steel is insufficiently alloyed or poorly heat treated.

In view of the lower velocity of HEP shell as compared to kinetic energy projectiles, errors in range estimation assume more serious proportions than in the case of kinetic energy shot. The probability of hitting the target, particularly at longer ranges, is thus lower with HEP shell than with kinetic energy shot.

Chemical energy armor-defeating ammunition do, however, have one very great advantage over kinetic energy projectiles. Since they generate their destructive energy upon impact against the target, chemical energy shell inflict as much damage when hitting from long ranges as from short ranges, whereas kinetic energy projectiles become less and less effective as the range from which they are fired increases.

The jet generated by the hollow charge (HEAT) shell continues in a relatively straight line along the line of flight of the shell, consequently the armor penetration performance of this type of ammunition closely follows the cosine law. The penetration performance of kinetic energy projectiles follows the cosine law fairly well up to approximately 30° obliquity, but at higher obliquities the deviation is very considerable and is markedly influenced by the geometrical and metallurgical design of the shot. Since the HEAT shell does follow the cosine law, a round which can penetrate 12" thick plate at normal obliquity can defeat 6" thick plate inclined at 60° obliquity. For comparison, the 90MM HVAP M304 shot can defeat 12" thick plate at 0° obliquity at ranges up to approximately 1300 yards, but cannot defeat even 4" thick plate at 60° obliquity when fired at point blank range.

The presently available data on the armor penetration performance of HEAT shell indicate that the thickness of armor which can be penetrated

90% of the time is approximately 4 times the inside diameter of the cone.* This behavior holds over a wide range of obliquities up to possibly 70°. Thus a 90MM HEAT shell having a cone diameter of approximately 3" should be able to penetrate about 12" of armor. The data contained in Table II shows that the 90MM HEAT T108E15 shell can defeat 5" armor at 60° obliquity and 4" armor at 68° obliquity.

In the case of defeat of armor by kinetic energy and chemical energy HEP shell, more or less massive pieces of metal flying at considerable velocities become available to inflict damage behind the armor. In the case of HEAT shell, however, only a thin beam of tiny, incandescent particles emerges behind the armor. Personnel or equipment directly in the path of the jet will become casualties, but the damage may not necessarily be serious. In order, therefore, to insure that the emerging jet will possess a significant degree of lethality, it has recently been agreed that the jet must have a residual penetrating ability of 2" of armor after defeat of the main armor to be considered effectively lethal.

It was found early in World War II that spin stabilized HEAT shell fired from rifled guns suffered a 30 to 50% loss in penetration performance as compared to non-rotating shell. The centrifugal force of spin is sufficient to cause the jet to cone out and dissipate much of its energy. This factor led to the intensive development of fin-stabilized non-rotated HEAT shell. The depth of penetration of 4 times the cone diameter applies only to non-rotated shell.

The depth of penetration by HEAT shell is inversely proportional to the square root of the density of the material under attack, therefore the thickness of material required to defeat the attack is also proportional to the square root of its density. Since the weight of material varies directly as its density, the weight of material required to defeat HEAT shell varies directly as the square root of its density. Low density materials are thus more resistant, on a weight basis, than are high density materials. Thus aluminum and magnesium will offer better resistance to HEAT attack than will the same weight of steel armor. As commercially available at the present time, however, aluminum and magnesium alloys in section thicknesses comparable to 2" and more of steel are significantly inferior to steel armor in resistance to attack by kinetic energy projectiles. Glass has been found to be more resistant to penetration by HEAT ammunition than would be predicted by the density law and is, in fact, one of the best materials for this purpose.

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* The results of recent dynamic firing tests indicate that penetrations may be as low as 2.8 cone diameters, while static firing tests with some types of HEAT ammunition have yielded penetrations as high as 6 cone diameters.

In their present stage of development, fin-stabilized HEAT shell do not match the accuracy of kinetic energy projectiles, and this, coupled with their lower velocities, results in lower hit probabilities than are possible with kinetic energy projectiles. The higher velocity and greater accuracy of kinetic energy projectiles make them considerably more accurate than all present types of chemical energy armor-defeating ammunition.

Performance of Kinetic Energy Projectiles Against Complex Armor Targets

Kinetic energy projectiles have been tested against spaced armor targets consisting of relatively thin (approximately 1/2") plates placed some distance in front of the more massive main armor. The function of the skirting plate is not to extract a significant amount of energy from the attacking projectile, but to so affect it by yawing, decapping, or fracturing the shot that its performance against the main armor is degraded.

Results of firing various types of 57MM and 90MM kinetic energy projectiles against spaced armor targets are shown in Table III. These tests were conducted at Aberdeen Proving Ground under the technical supervision of the Watertown Arsenal. Photographs of the projectiles were also taken as they emerged behind the skirting plate in order to observe the effect of the skirting plate on the projectiles.

It was found that 57MM AP and APC shot were not fractured by passage through 1/2" thick skirting plate but were considerably yawed. In addition, the cap was always removed from the APC shot. Surprisingly, the 90MM AP shot were found to be readily fractured by passage through 1/2" thick skirting plate. Since the 57MM shot were not fractured, parallel plate arrangements were found to be worse than the basic armor since the shot were yawed in the direction of lower obliquity against the main armor. Oppositely sloped spaced armor arrangements are indicated for cases where the shot cannot be fractured by the skirting plate.

Since the 90MM AP shot was broken by the skirting plate, both parallel and non-parallel placement of the skirting plate were equally effective in degrading this shot. The 90MM APC shot was not readily fractured by skirting armor, but its performance was degraded against the target conditions shown in Table III because, once its cap was removed, it behaved essentially the same as monobloc shot, and the target conditions chosen, namely 30° and 40° obliquity, are those where monobloc shot are less effective than capped shot.

Tungsten carbide cored projectiles may be seriously degraded by spaced armor arrangements since the very brittle core may be rather easily fractured by skirting plates. Once the core is fractured prior to impact against the main armor, the HVAP type of shot is rendered comparatively ineffective.

It is essential that spaced armor arrangements to defeat kinetic energy projectiles be very carefully chosen, because it is entirely possible that some arrangments cause the projectile to penetrate far more efficiently than it would against the main armor alone.

Spaced armor arrangements can readily be designed to fracture capped shot. This can be done by using two skirting plates separated from each other. The first skirting plate removes the cap and the second fractures the shot. The test described in Table III, where the 90MM APC T50 was fired against two 1/2" thick plates parallel to and separated from each other and the main plate (3" at 55°) by 8" of space shows what can be done with this type of plate arrangement. This arrangement could not be defeated even at point blank range, whereas 4" armor at 55° obliquity can be defeated by the same projectile at ranges up to 600 yards and 3" armor at 55° at ranges up to 1600 yards.

Performance of Chemical Energy Projectiles Against Complex Armor Targets

Since the HEP shell defeats armor by the application of a severe shock which induces stress waves of high magnitude, it is obvious that the best way to cope with the attack of this type of ammunition is to prevent the shock wave from getting started in the armor. It does not help much to increase the thickness of the plate since large increases in thickness are required to defeat HEP shell. The British have done an extensive amount of firing of HEP shell against spaced armor structures and have found that they could be readily defeated by spaced armor combination, by rubber pads placed between armor sandwiches, etc. The skirting plate of spaced armor arrangements designed to defeat HEP shell must be supported well enough to prevent contact with the main armor during detonation of the shell, since then the shock wave will be transmitted to the main armor.

Table IV contains some data recently obtained at Aberdeen Proving Ground on the performance of the 105MM HEP T81E17 shell against 3" armor at 55° and then against a spaced armor combination consisting of a 1/2" plate 8" in front of the 3" armor at 55°. This shell can normally defeat 5" plate at this obliquity. Its inability to defeat a spaced armor combination consisting of a total of 3-1/2" thickness of steel indicates how greatly this type of shell can be degraded by spaced armor.

There has been extensive work on the development of defense against HEAT shell. This type of ammunition can penetrate such a great thickness of solid steel that other means must be found to defend against it. Since it was apparent that low density materials offered better protection against HEAT shell for a given weight of material, a considerable amount of effort was expended during World War II in developing low density materials for this purpose. The best low density material developed was HCR-2 which consists of a mixture of quartz gravel in a mastic base of 75% asphalt and 25% wood flour. This material when placed behind a thin steel plate and attached to the main armor of vehicles was found to give much better protection against HEAT shell than a similar weight of steel or other materials with the exception of solid or laminated glass.

Another type of defense against the HEAT round was provided by fixing 7" to 8" long closely spaced steel spikes to the surface of the main armor; the function of the spikes being to break up the cone before initiation of the jet. Spiked armor structures have been found to be effective against several models of HEAT rounds.

More recent developments sponsored by the Detroit Arsenal show that an arrangement of parallel angle irons, made of armor steel, placed on the surface of the main armor offer considerably increased protection, particularly at high angles of attack, against both HEAT and HEP shell. Although these angle irons did not defeat all the HEAT shell fired at them, they were effective in significantly reducing the probability of a perforation when hit by a HEAT shell.

It was found during World War II that spin stabilized HEAT shell could be fairly readily defeated by spaced armor due to the degrading effect of the spin, particularly when the standoff was increased by the spaced armor. More recent tests have shown that spins even as low as 10 rev./sec. result in a 20% decrease in penetration performance of 105MM HEAT shell against a spaced armor target consisting of a 3/4" plate 12" in front of the main armor. This 20% decrease represented degradation in performance of the same round compared to its performance against the same target when the shell was not rotated.

Very recently, tests of the 3.5" HEAT M28 rocket and the 90MM HEAT T108E20 shell have been conducted against spaced armor targets. The basic armor consisted of 4" plate at 40° obliquity; firings were first conducted at this target, then at spaced armor targets consisting of a 1/2" thick plate parallel to and 8" in front of the main armor. In one case a 3" plate was placed behind the 4" armor, with 1/4" thick plates stacked behind the 3" plate in order to measure the residual penetrations, but in all other cases, a series of 1/4" thick plates were stacked directly behind the main armor for this purpose.

Figure 7 tabulates the data resulting from the tests described above. Starting at the lefthand end of the chart, 14 rounds of the 3.5" rocket were fired against 4" armor at 40° obliquity. Eleven rounds completely perforated the 4" plate and achieved residual penetrations of 3" to 3-5/8" into the 3" and 1/4" thick plates behind the 4" plate. Three rounds appeared to produce low order detonations; the 4" target, however, was perforated, but relatively little residual penetration into the 3" back-up plate was achieved.

Nineteen rounds of the 3.5" rocket were then fired at spaced armor consisting of the 1/2" skirting plate parallel to and 8" in front of the 4" plate. Of these nineteen rounds, four failed to perforate the 4" main armor, three perforated the 4" main armor but had no residual penetration ability, three more perforated, but had residual penetration abilities of less than 1", three achieved residual penetrations of 1 to 1-1/2" in depth, and the remaining six rounds achieved the same residual penetrations as were obtained against the solid armor target.

The performance of the 90MM HEAT T108E20 was found to be very variable against a simple armor target consisting of 4" plate at 40° obliquity. Of ten rounds fired, all perforated the target, but the residual penetrations varied from 2" to 5-3/8". When tested against spaced armor with 8" spacing, two rounds of eight 90MM T108E20 shell fired failed to defeat the target. Four rounds perforated the target and achieved residual penetrations of the same order of magnitude as were obtained against the solid armor target, while two rounds achieved even higher residual penetrations; 6-1/2" to 7" in depth. This increase in residual penetration probably resulted from a more efficient standoff caused by the 8" spacing.

A 16" spacing between the skirting armor and the main plate greatly improved the effectiveness of spaced armor against the 90MM HEAT T108E20 shell. Of ten rounds fired, four were totally defeated, 4 perforated but achieved residual penetrations of but 1/4" to 1" in depth, while only two rounds performed as well as they did against the main armor alone.

While the above tests are only elementary in nature, there appears good hope that spaced armor combinations may be devised which will be even more successful against HEAT shell. Spaced armor may be particularly effective at higher obliquities of attack.

Combinations of the main steel armor, low density materials such as glass, and spaced armor may yet provide real defense against chemical energy armor-defeating ammunition.

In conclusion, the thought should be expressed that both types of armor-defeating ammunition should be brought to the field of battle. Any decision to adopt one type of the kinetic and chemical energy ammunition to the exclusion of the other type would greatly simplify the enemy's armored vehicle design and construction problems. It is possible to devise a reasonably simple defense against either type of ammunition alone, but the problem of defense against both types together is an extremely complicated one.

A. HURLICH
Metallurgist

TABLE I

Penetration Performance of 90MM AP T33, 90MM APC T50, and 90MM HVAP M304 vs Rolled and Cast Homogeneous and Face-Hardened Armor

Armor				Ballistic Performance of 90MM AP T33		90MM APC T50		90MM HVAP M304	
Thickness, in.	Type	BHN*	Obl. of Attack	Bal. Lim. f/s	Max. Range yds	Bal. Lim. f/s	Max. Range yds	Bal. Lim. f/s	Max. Range yds
3	RH	280	45°	1983	>5000	2216	3975	----	----
3	RH	280	60°	2629	2200	2853	1300	3145	1575
3	RH	280	65°	3026	625	3101	350	3543	675
3	RH	320	60°	2645	2150	2795	1550	3246	1350
3	RH	320	65°	2870	1225	>3109	<350	3611	525
3	CH	260	45°	1979	>5000	----	----	2437	3225
3	CH	260	53°	2315	3550	----	----	2725	2550
3	CH	280	55°	2313	3550	----	----	2754	2475
3	CH	280	60°	2586	2400	2683	2000	----	----
3	CH	280	65°	----	----	3112	325	----	----
3	CH	280	70°	3073	375	----	----	----	----
3	FH	---	55°	2059	4725	2248	3825	----	----
3	FH	---	60°	2505	2725	2635	2175	2903	2125
3	FH	---	65°	2648	2125	2902	1100	>3300	<1225
4	RH	280	30°	2054	4750	2149	4275	----	----
4	RH	280	45°	2469	2875	2831	1400	----	----
4	RH	280	55°	2742	1750	3010	700	3571	625
4	RH	280	60°	3079	450	>3162	<125	>3638	<475
4	RH	320	55°	2719	1850	3138	225	3503	775
4	RH	320	60°	3075	450	----	----	>3748	<225
4	RH	360	60°	2943	975	3097	375	>3680	<375
4	CH	240	55°	2785	1575	----	----	----	----
4	CH	240	60°	2933	1000	>3208	Above MV	>3800	<100
4	CH	280	55°	2620	2250	2744	1750	----	----
4	CH	280	60°	3007	700	>3135	<250	----	----
4	CH	280	65°	3129	250	----	----	----	----
4	CH	320	60°	2947	950	3175	75	3669	400
4	FH	---	45°	----	----	2391	3200	2868	2225
4	FH	---	50°	----	----	----	----	3160	1550
4	FH	---	55°	----	----	2765	1650	>3397	<1000
4	FH	---	60°	2763	1675	3069	475	----	----
5	RH	240	30°	2804	1500	2343	3400	----	----
5	RH	240	45°	3146	200	2976	825	----	----
5	RH	320	30°	2967	875	2461	2925	----	----
5	RH	320	45°	3167	100	>3177	<75	----	----

* BHN- Brinell Hardness
> Greater than
< Less than

MV - AP, APC - 3200 f/s
MV - HVAP - 3850 f/s

RH - Rolled homogeneous armor
CH - Cast homogeneous armor
FH - Face-hardened armor

TABLE I (Con'd.)

Thickness, in.	Type	BHN*	Obl. of Attack	90MM AP T33 Bal. Lim. f/s	90MM AP T33 Max. Range yds	90MM APC T50 Bal. Lim. f/s	90MM APC T50 Max. Range yds	90MM HVAP M304 Bal. Lim. f/s	90MM HVAP M304 Max. Range yds
5	CH	240	30°	2543	2575	2234	3900	----	----
5	CH	240	45°	2740	1750	2905	1100	----	----
5	FH	---	30°	2475	2850	2394	3175	2819	2325
5	FH	---	45°	2866	1250	2879	1200	3208	1425
6	RH	260	30°	> 3214	Above MV	2750	1725	2562	2925
6	CH	240	30°	2907	1100	2632	2200	2487	3100
6	FH	---	30°	----	----	2863	1275	3333	1150
7.6	RH	260	30°	----	----	> 3182	< 50	2892	2150

TABLE II

Penetration Performance of HEAT Shell Against Armor

Projectile	Thickness of Armor	Obliquity of Attack	No. of Rounds Fired	Results
90MM HEAT* T108E15	Approx. 5"	60°	5	3 complete penetrations 2 partial penetrations
"	4.1"	68°	1	Complete penetration
"	3.4"	73°, 75°	2	Ricochet, no penetrations
"	4.5"	72°	1	Ricochet, no penetration

* fired from range of 50 yards, 2400 f/s muzzle velocity

TABLE III

Performance of Kinetic Energy Projectiles Against Spaced Armor Combinations

Projectile	Main Armor* Thickness	Main Armor* Obliquity	Thickness Skirting Plate	Arrangement**	Spacing	Ballistic Performance: Ballistic Limit f/s (Protection)	Ballistic Performance: Maximum Range for Penetration - yards
57MM AP M70	2"	40°	None	-	-	1997	1850
"	2"	40°	1/2"	A	16"	1772	2500
"	2"	40°	1/2"	B	16"	2620,2538	175
57MM APC M86	2"	40°	None	-	-	2149	1500
"	2"	40°	1/2"	A	16"	1943,1940	2000
"	2"	40°	1/2"	B	16"	2755	Above m.v.
90MM AP T33	3"	55°	None	-	-	2505	2725
"	3"	55°	1/2"	A	8"	2952	950
"	4"	30°	None	-	-	2025	4875
"	4"	30°	1/2"	A	16"	2383	3250
"	4"	30°	1/2"	A	8"	2368	3300
90MM APC T50	3"	40°	None	-	-	2040	4800
"	3"	40°	1/2"	A	16"	2452	2950
"	3"	40°	1/2"	A	8"	2501	2750
"	4"	30°	None	-	-	2171	4200
"	4"	30°	1/2"	A	16"	2681	2000
"	4"	30°	1/2"	B	16"	2657	2100
"	4"	30°	1/2"	A	8"	2669	2050
"	3"	55°	None	-	-	2777	1600
"	3"	55°	3/4"	B	20"	2657	2100
"	3"	55°	two 1/2" plates 8" apart	A	8"	partial at 3249	Above m.v.

TABLE III (Con'd.)

Performance of Kinetic Energy Projectiles Against Spaced Armor Combinations

Projectile	Main Armor* Thickness	Main Armor* Obliquity	Thickness Skirting Plate	Arrangement**	Spacing	Ballistic Performance: Ballistic Limit f/s (Protection)	Ballistic Performance: Maximum Range for Penetration - yards
90MM HVAP M304	3"	55°	None	-	-	3018	1850
"	3"	55°	1/2"	A	8"	3832	50
"	4"	30°	None	-	-	2226	3750
"	4"	30°	1/2"	A	8"	2690	2625
"	4"	30°	1/2"	A	16"	2780	2425
"	4"	30°	1/2"	B	16"	2702	2600
"	6"	30°	None	-	-	2590	2900
"	6"	30°	1/2"	A	12"	3689	350

* Main armor is rolled homogeneous plate of 260-280 BHN.

** Arrangement:

A - Skirting plate parallel to main armor

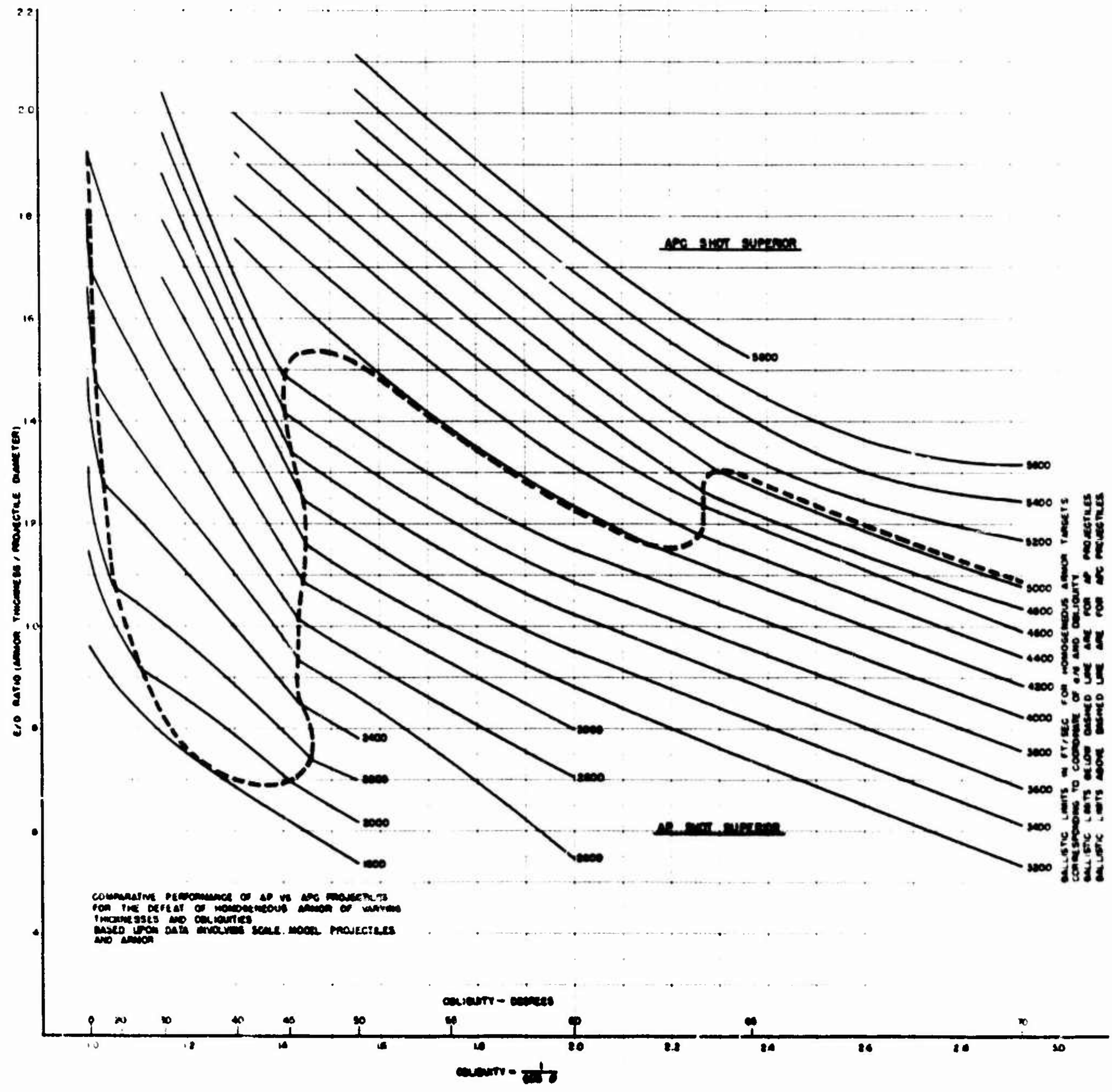
B - Skirting plate and main armor sloped towards each other, each inclined at same angle but in opposite directions from normal.

TABLE IV

Performance of HEP Shell Against Spaced Armor Combinations

Projectile	Main Armor Thickness	Main Armor Obliquity	Thickness Skirting Plate	Arrangement	Spacing	Result on Target
105MM HEP T81E17	3"	55°	None	-	-	Average spall size 10" x 7"
"	3"	55°	1/2"	parallel	8"	No spalling, target not defeated

The 105MM HEP T81E17 shell is normally capable of spalling 5" thick rolled homogeneous armor.



COMPARATIVE PERFORMANCE OF AP VS APC PROJECTILES FOR THE DEFEAT OF HOMOGENEOUS ARMOR OF VARYING THICKNESSES AND OBLIQUITIES
BASED UPON DATA INVOLVING SCALE MODEL PROJECTILES AND ARMOR

WATERTOWN ARSENAL LABORATORY
RESTRICTED

~~FIGURE 11~~

WTN.639-8646

SECURITY INFORMATION

Figure 1

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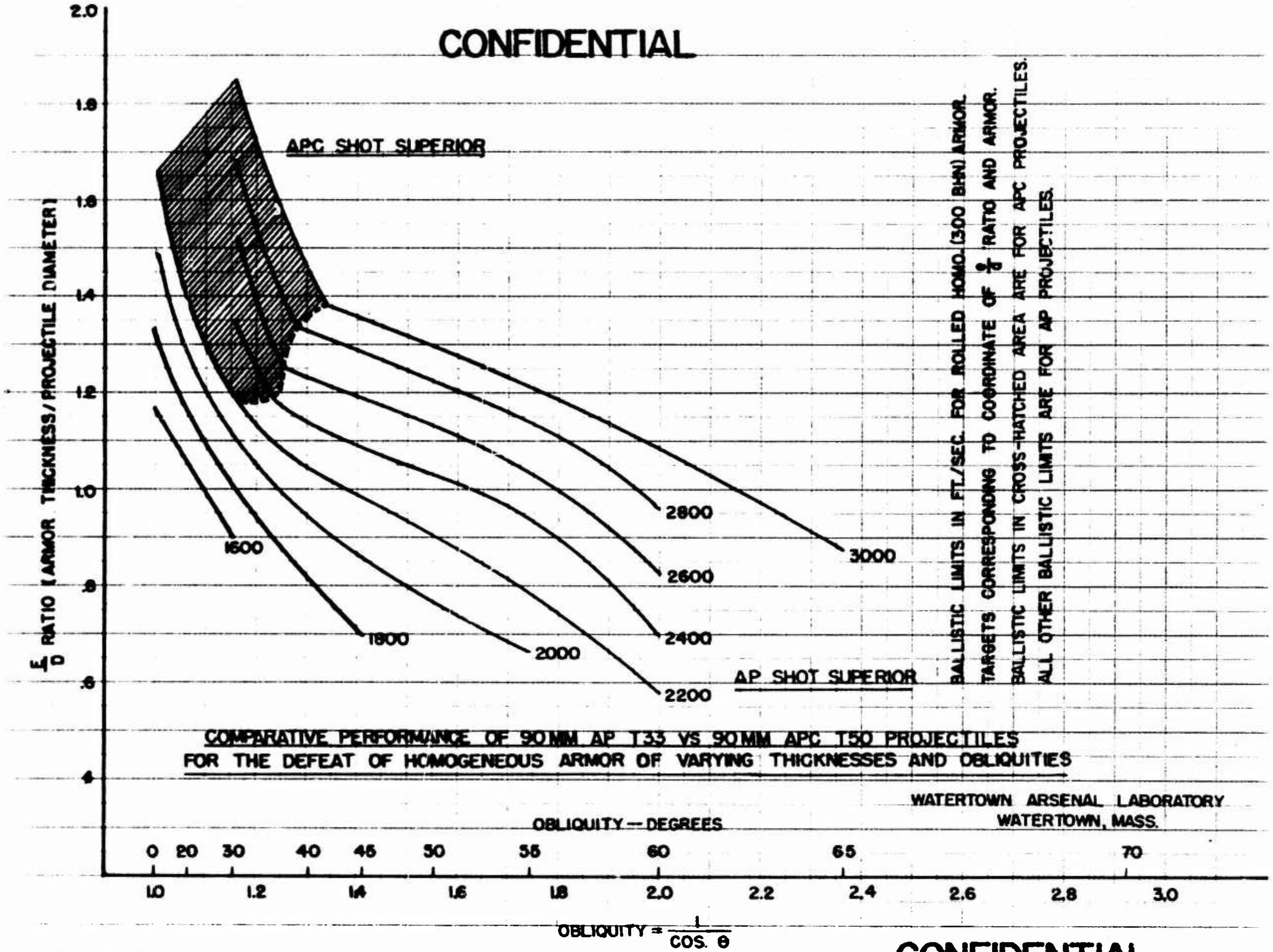

COMPARATIVE PERFORMANCE OF 90MM AP T33 VS 90MM APC T50 PROJECTILES FOR THE DEFEAT OF HOMOGENEOUS ARMOR OF VARYING THICKNESSES AND OBLIQUITIES

WATERTOWN ARSENAL LABORATORY
WATERTOWN, MASS.

WTN.639-11,504

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FIGURE 2

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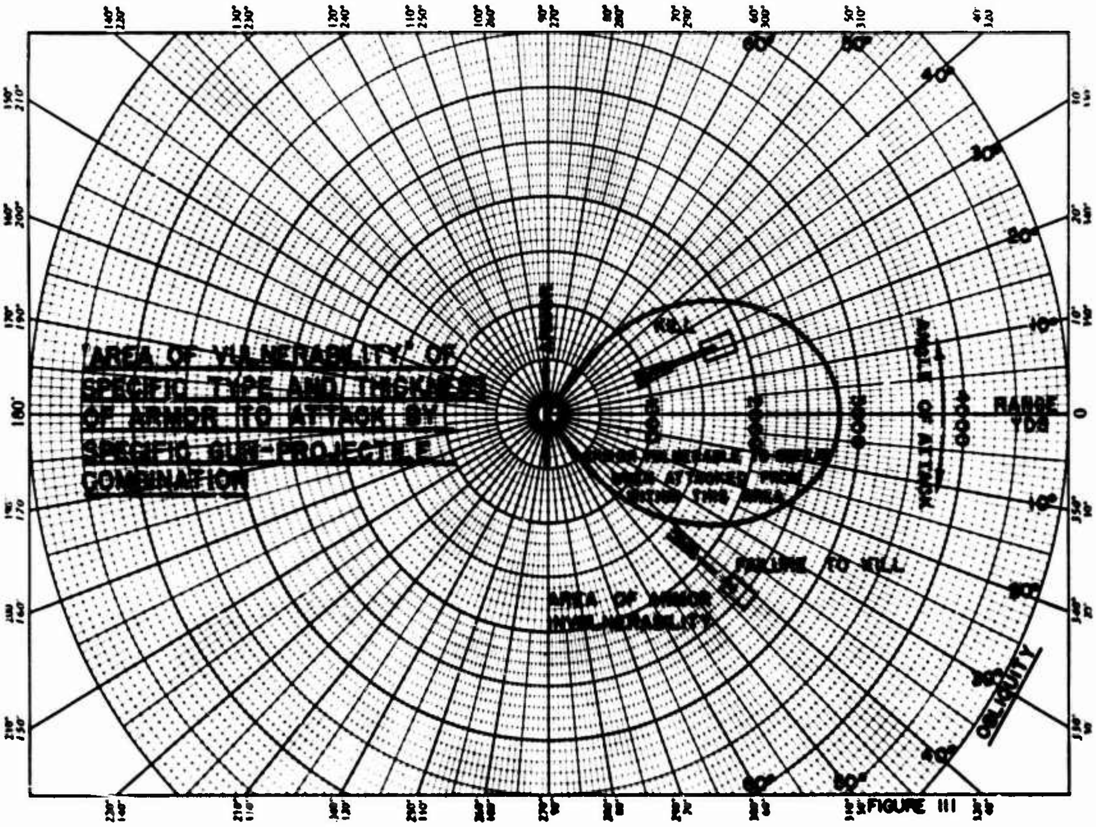
SECURITY INFORMATION



~~FIGURE III~~ SCHEMATIC AREA OF VULNERABILITY CURVE WTN.639-10,559

FIGURE 3

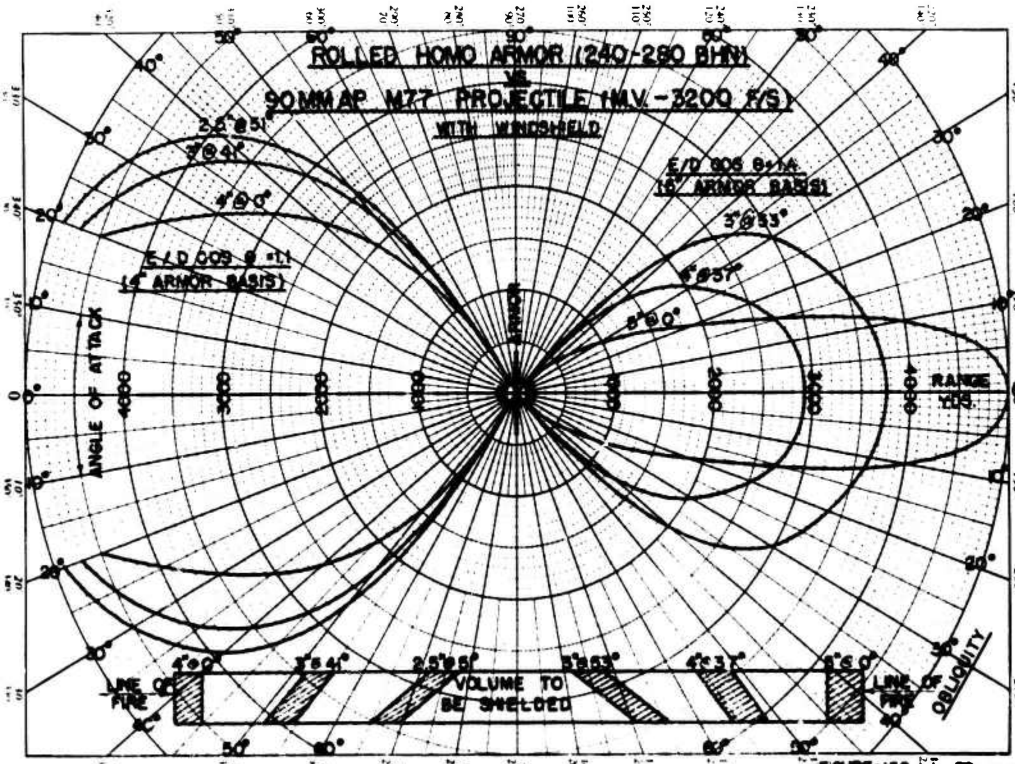


FIGURE 4

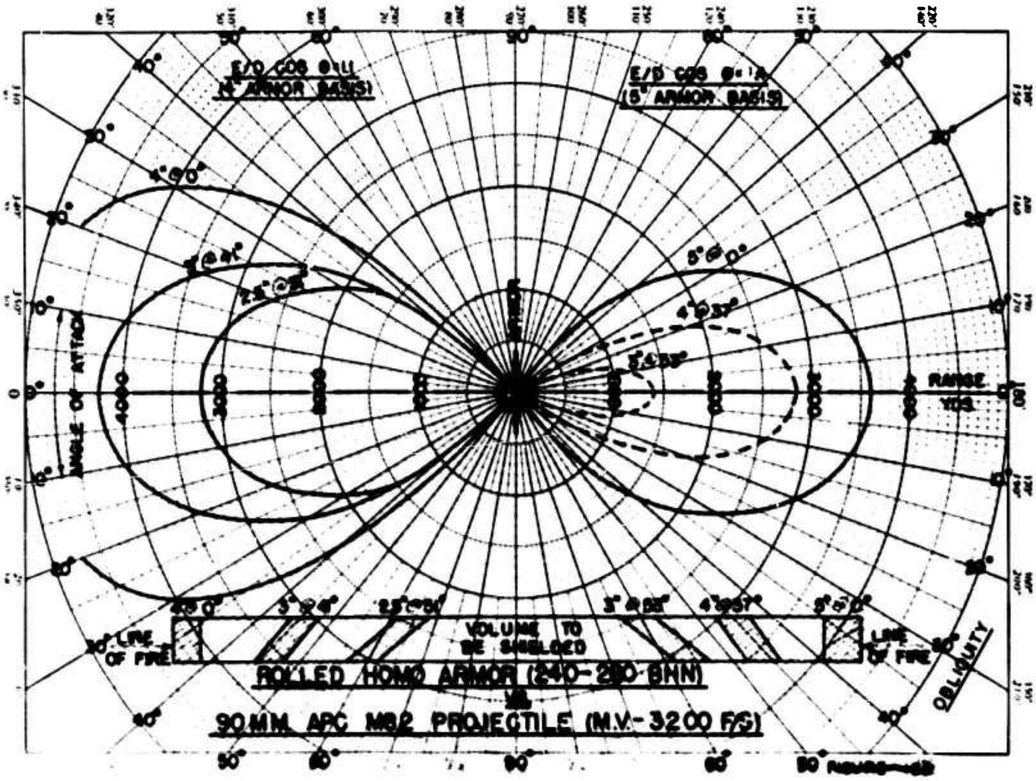
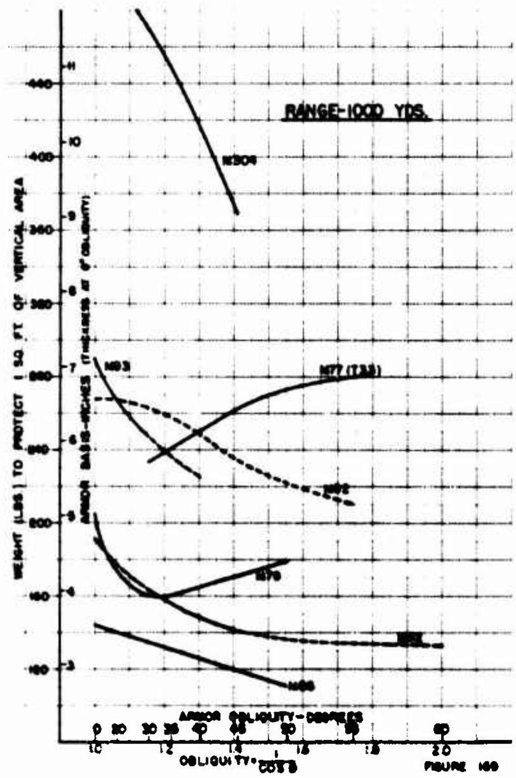
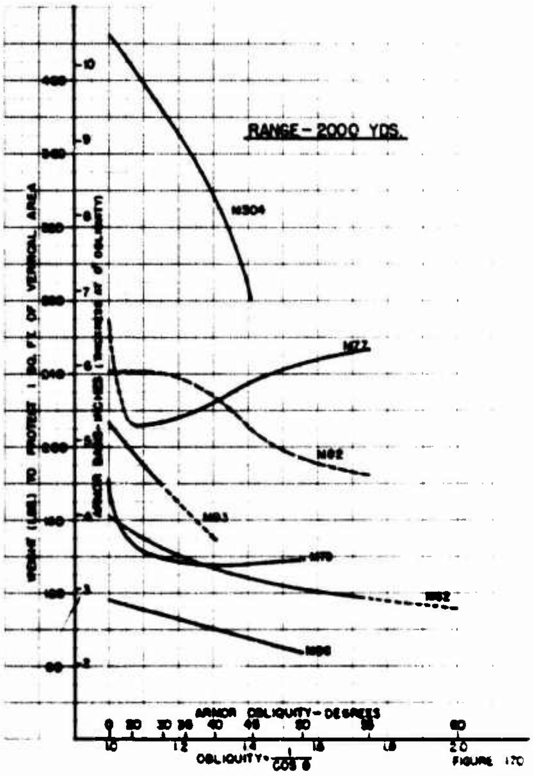


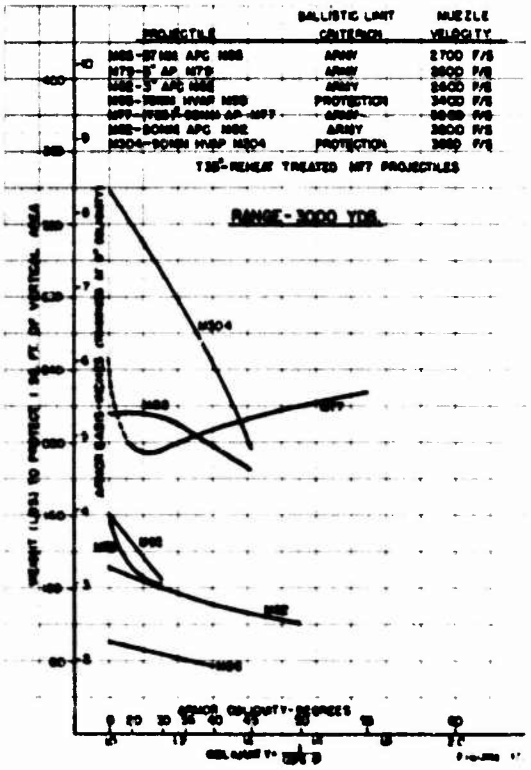
FIGURE 5

WATERTOWN ARSENAL LABORATORY

FIGURES 152 – 153 COMPARISON OF AREAS OF VULNERABILITY FOR VARIOUS COMBINATIONS OF ARMOR THICKNESS AND OBLIQUITY HAVING EQUAL WEIGHT PER UNIT OF SHIELDED VOLUME WHEN ATTACKED BY 90MM STEEL PROJECTILES. WTN.639-1C,651







~~FIGURES 169 — 171~~ WEIGHTS OF ROLLED HOMOGENEOUS ARMOR AT VARIOUS OBLIQUITIES REQUIRED TO PROTECT ONE UNIT OF VERTICAL AREA AGAINST VARIOUS PROJECTILES AT SELECTED RANGES.

WTN.639-12,003

FIGURE 6

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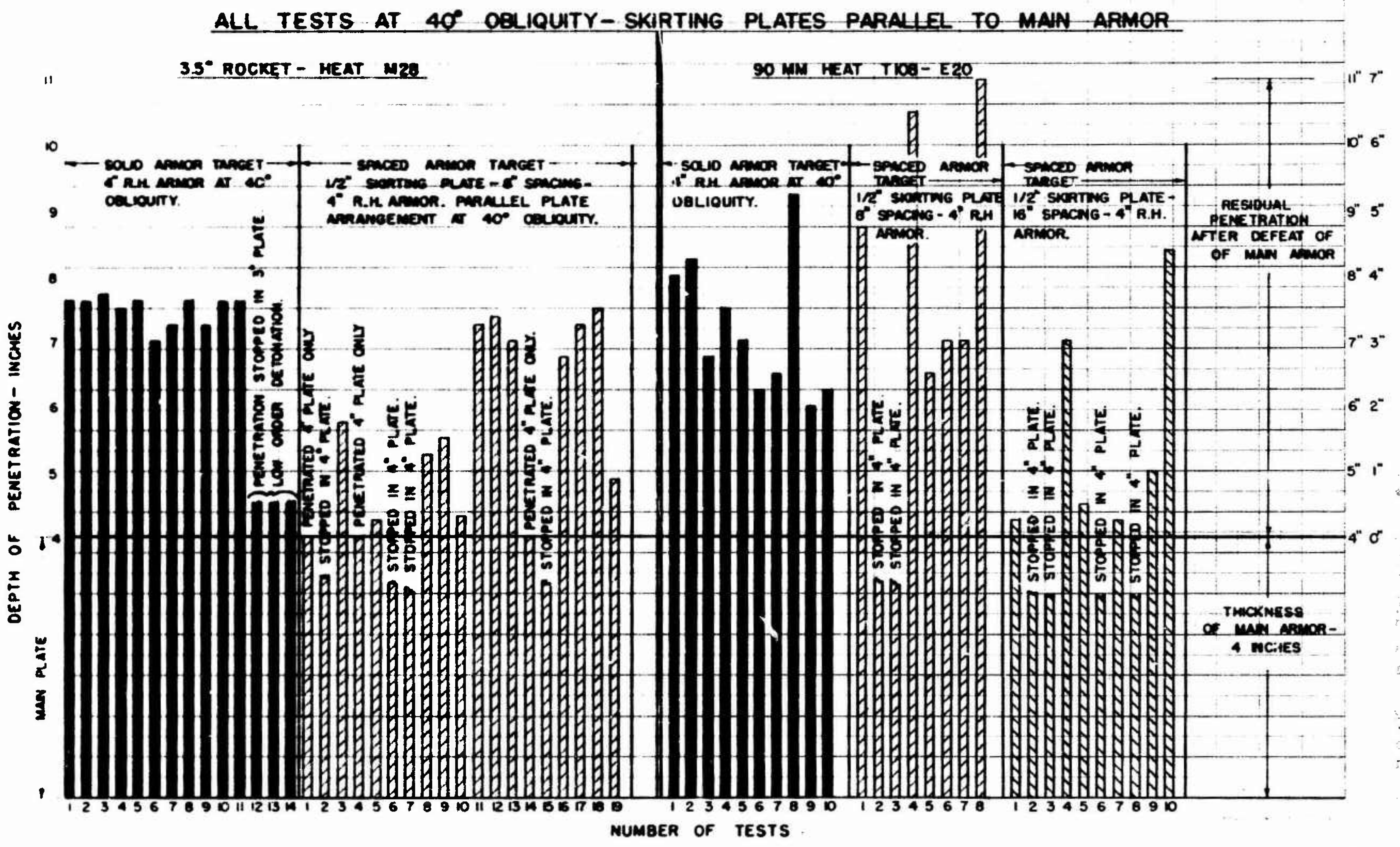

ALL TESTS AT 40° OBLIQUITY – SKIRTING PLATES PARALLEL TO MAIN ARMOR

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FIGURE 7

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MATION