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WATERTOWN ARSENAL LABORATORIES

BALLISTIC EVALUATION OF ROLLED HOMOGENEOUS STEEL ARMOR WITH TUNGSTEN CARBIDE AND TITANIUM CARBIDE FACING (U)

TECHNICAL REPORT NO. WAL TR 161.3/1 (C)

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BY

DOMINIC A. PICCIONE

DECEMBER 1960

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OMS CODE 5010.11.[illegible] - MATERIALS FOR ARMOR AND PROTECTION AGAINST OTHER HAZARDS

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Terminal ballistics, testing

Ballistic limits - protection

BALLISTIC EVALUATION OF ROLLED HOMOGENEOUS STEEL ARMOR WITH TUNGSTEN CARBIDE AND TITANIUM CARBIDE FACING (U)

Technical Report No. WAL-TR-161.3/1(C)

By

Dominic A. Piccione

Dec[illegible]60

OMS CODE 5010.11.8090051 - Materials for Armor and Protection against other Hazards

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TITLE

BALLISTIC EVALUATION OF ROLLED HOMOGENEOUS STEEL ARMOR WITH TUNGSTEN CARBIDE AND TITANIUM CARBIDE FACING (U)

ABSTRACT (U)

(C) Ballistic testing was conducted to determine the comparative performance of tungsten carbide steel and titanium carbide steel composite armor when attacked by cal. .40 H19B WC cores, cal. .50 AP M2 projectiles, 20MM fragment simulating projectiles, and cal. .40 AP T33 scale model projectiles, at various obliquities. On an areal density basis the TiC composite armor was approximately equivalent to steel, while the WC composite armor was inferior to steel. The results obtained do not justify consideration of these armor configurations for Ordnance applications.

Dominic A. Piccione
DOMINIC A. PICCIONE
Mechanical Engineer

APPROVED:

J. F. Sullivan
J. F. SULLIVAN
Director
Watertown Arsenal Laboratories

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INTRODUCTION (U)

(C) Kennametal Corporation, under Contract DA-19-066-ORD-2641, conducted preliminary tests to determine the effectiveness of tungsten carbide (WC) and titanium carbide (TiC) facing on steel armor for the defeat of steel and tungsten carbide projectiles. Cal. .40 steel and WC projectiles were fired at 1-3/4-inch-thick steel armor, placed at 30° obliquity, without facing and with 1/4-inch-thick WC and TiC facings. The results obtained indicated that the use of a hard facing material might improve the ballistic performance of steel armor. It must be pointed out, however, that for these tests the difference in areal density between the uncoated and coated plates was not taken into account. No direct comparison could be made between the composite armor and solid steel of the same areal density since the ballistic limits were above the muzzle velocity of the available guns.

(U) In order to evaluate fully the effect of such facing materials, Watertown Arsenal Laboratories has conducted a series of ballistic tests to determine the comparative ballistic performance of WC and TiC facings placed on rolled homogeneous steel armor.

MATERIALS (U)

(U) Tungsten carbide facings of 1/16" and 1/8" thicknesses and titanium carbide facings of 1/16", 1/8" and 1/4" thicknesses were employed in the form of hexagonally shaped platelets (Figure 1) measuring 0.425" across the flats. The tungsten carbide consisted of 85% WC + 15% Co nominal composition cold pressed and sintered to a hardness of 88 Rockwell A, while the titanium carbide consisted of 70% TiC + 30% Ni which was cold pressed and sintered to a hardness of approximately 87 Rockwell A.

(U) Rolled homogeneous steel armor of various thicknesses was cut to 12" x 12" sizes. Each plate was Blanchard ground to a thickness such that a predetermined areal density would be obtained. All steel armor employed had previously been quenched to martensite and tempered to a hardness of 300 Bhn subsequent to meeting the requirements of Specification MIL-A-12560. Chemical composition of the steel armor is contained in Table I.

(U) Both types of facing materials and the steel armor were sandblasted to obtain the clean surfaces necessary for satisfactory bonding. Neither facing nor steel was handled with bare hands subsequent to sandblasting since oils and moisture transferred to the materials in handling would prevent adequate bonding during brazing. A 1"-wide steel frame was placed along the perimeter of the plate to prevent the facing material from "floating" off during the brazing operation. Two 6" x 12" strips of 0.005"-thick silver solder, having the composition shown in Table I, were placed on each plate and flux applied. The platelets were positioned, each plate requiring the placing of approximately 700 individual pieces.

The entire assembly was then placed for two hours in a furnace which had been preheated to 1375°F. The plates were air cooled from the furnace with no evidence of excessive warping even though the rate of expansion of steel is about twice that of the facing materials used. Photographs of two plates taken prior to ballistic testing are shown in Figures 2 and 3.

(U) As a result of the brazing operation, the steel plate was softened to an average Brinell hardness of 211. Metallographic examination of the steel revealed that it still consisted of a tempered martensitic structure which indicates that the original structure was not destroyed by the high brazing temperature since the austenitizing temperature was not exceeded. Photomicrographs representing three steel plates are presented in Figure 4.

(U) Ballistic data were obtained using 20MM fragment simulating projectiles, caliber .40 H19B WC cores, caliber .50 AP M2 projectiles, and caliber .40 AP T33 scale model projectiles, at various obliquities. The WC cores were cold pressed and sintered from 87% WC + 13% Co to a hardness of 89 Rockwell A. The scale model projectiles were machined from FXS-318 steel, water quenched and stress relieved to a hardness of 63 Rockwell C, followed by base tempering to develop a hardness gradient to 45 Rockwell C at the base. The caliber .50 AP M2 projectiles were standard rounds. Drawings of all projectiles are presented in Figure 5.

BALLISTIC TEST PROCEDURE (U)

(U) The detailed outline of the ballistic test conditions is presented in Table II.

(U) Ballistic testing was conducted to determine protection-ballistic limits* consisting of the two highest partial penetrations and the two lowest complete penetrations within a velocity spread of 125 fps. When the velocity spread was greater than 125 fps or when insufficient rounds had been fired, a two-round ballistic limit was computed. Care was exercised after each round fired to insure that the next round would impact a plate area where the platelets had not been removed by a previous impact. A 0.100"-thick sheet of Hadfield-Manganese steel, having a hardness of 40 Rockwell C, was placed in front of the facing to confine the facing during impact.

*Complete penetration occurs when plate and/or projectile fragments penetrate a 0.020"-thick sheet of Duralumin placed 6" behind the armor.

RESULTS AND DISCUSSION (U)

(U) The ballistic data obtained both by Watertown Arsenal Laboratories and Kennametal Corporation are presented in Table III. Round by round results are presented in Appendix A.

Ballistic Performance of WC-Steel Armor (U)

(C) Ballistic data obtained with caliber .40 AP T33 scale model projectiles are plotted as a function of areal density in Figure 6. On the average, the hard-faced armor was approximately 6% inferior to steel targets of equal areal densities. Hadfield-Manganese sheet had been used for the 45 degree test condition while none had been used for the 30 and 60 degree test conditions. The curves clearly show that the hard-faced armor was nearly equivalent to the steel except for one 30 degree and three 45 degree obliquity conditions. These data did not fit the curve, falling far below the data obtained. As this anomaly was noted elsewhere a discussion will be presented in a following section. It suffices to say that the limited data obtained does not indicate that the hard-faced armor will offer any significant increase in protection.

(C) A graphical presentation of the limited ballistic data obtained with caliber .50 AP M2 projectiles is presented in Figure 7. This curve clearly shows the inferiority of the composite armor. At 30 degrees obliquity there is a difference of 1372 fps in the ballistic limit, which represents a 48% difference in performance between the hard-faced armor and equivalent steel targets. On an areal density basis the composite armor averaged approximately 43% inferior to solid steel armor.

(C) Ballistic data obtained with caliber .40 H19B WC cores is plotted versus obliquity in Figure 8. From this graph it is obvious that the difference in performance is slight. The ballistic limits ranged from 12 - 660 fps less than those of equivalent steel targets. This represents an average difference in performance of approximately 8%.

Ballistic Performance of TiC-Steel Armor (U)

(C) Ballistic data obtained with caliber .40 AP T33 scale model projectiles is plotted as a function of areal density in Figure 9. On the average, the hard-faced armor was approximately 2% superior to steel targets having the same areal density. Inspection of the data reveals that at an equivalent thickness of 0.700" the 30 and 45 degree ballistic limits were less than those at 0.600" equivalent thickness. If these anomalous data points are ignored, the composite armor would still be only 5% superior to equivalent steel targets, representing at best a marginal improvement.

(C) Ballistic data obtained with 20MM fragment simulating projectiles is plotted versus areal density in Figure 10. The limited data obtained indicates that the hard-faced armor is approximately 14% inferior to steel targets of the same areal density. Inspection of the curves reveals that the ballistic limits for the hard-faced armor ranged 300 - 862 fps less than those of equivalent steel targets. At only one condition, where no ballistic limit was obtained for the hard-faced armor, did it show any indication of being superior to solid steel targets. Even at this point it is estimated that the hard-faced armor would have been less than 10% superior to a steel target of equal density. This statement is based on the fact that a complete penetration was almost obtained, indicative that the ballistic limit was nearly reached. From the data obtained a two-round Army ballistic limit* of approximately 4180 fps can be estimated.

Effect of Brazing (U)

(C) Photographs of five plates, two with WC facing and three with TiC facing, are shown in Figures 11 through 15. Figures 11 and 12 are examples of poor brazing since 85% of the platelets were removed as a result of only three impacts. Examples of good brazing can be seen in Figures 13 through 15. One plate withstood the impact of twelve rounds while another withstood six rounds, each round causing the removal of only small localized areas of platelets. The third plate represents an extreme condition of attack, 20MM fragment simulating projectiles at 60 degrees obliquity. Even under this severe test condition the facing withstood six impacts.

(C) Photomicrographs of three randomly selected brazed joints are shown in Figure 16. These photomicrographs show the presence of many large voids and evidence of flux entrapment. This would indicate that in order to obtain a uniform bond, free of these defects, the brazing should be done in an inert atmosphere or a vacuum. It is felt, however, that the bond obtained was adequate to permit reliable ballistic testing since all but 7 plates withstood the impact of 5 or more rounds.

GENERAL CONSIDERATIONS (U)

(C) It was previously mentioned that at several test conditions the ballistic data indicated decreasing ballistic resistance with increasing thickness of the hard facing. Since the object of this study is to determine whether the use of hard facing will significantly improve the ballistic performance of armor, it is beyond the scope of this report to explain this anomalous behavior. However, a possible reason for the behavior follows.

*Complete penetration occurs when light or the projectile can be seen from the rear of the plate.

(C) It has been demonstrated by many investigators that projectile nose-shatter generally occurs at obliquities greater than about 25 - 30 degrees at velocities above a certain minimum for the projectile and plate thickness involved.[1,2,3] The shatter tendency for a given projectile increases with increasing velocity, increasing plate hardness, or increasing plate thickness. When a projectile suffers nose-shatter, it achieves penetration by a shear or punching mechanism involving a minimum of plastic deformation. The energy required for this plugging or punching process is largely dependent on the armor plate thickness at a constant obliquity of attack. Furthermore, for a constant obliquity, the velocity at which shatter occurs is very sensitive to plate thickness. Hence, it is conceivable that the projectile nose fractured into a very few large fragments against the 0.600" equivalent steel thickness armor, and shattered into many small fragments against the 0.700" equivalent steel thickness armor. It follows, then, that the penetration energies could be nearly equal, with the penetration of the thicker target possibly requiring less energy. The greater deformation around the penetrations of the 0.600" targets lend credence to this possibility.

(C) Although the use of a hard facing does not appear worthwhile for improvement of the ballistic performance of armor, the possibility of employing a hard material with a high neutron capture cross-section (such as boron carbide) for radiological protection should be investigated.

CONCLUSIONS (U)

(U) On the basis of the results obtained, the hard-faced armor is inferior to equivalent steel targets.

RECOMMENDATIONS (U)

(U) 1. Further ballistic testing of tungsten carbide and titanium carbide platelets is not recommended.

(C) 2. The use of hard facing placed over armor of specification hardness might increase the ballistic performance, but since the increase is expected to be marginal, ballistic testing of such an arrangement is not recommended.

(C) 3. The possibility of employing a hard material with a high neutron capture cross-section (such as boron carbide) for radiological protection should be investigated.

---

[1] *ZENER, C., Mechanism of Armor Penetration, Third Partial Report, Watertown Arsenal Laboratory, WAL 710/492-1, 30 March 1944.*

[2] *ABBOTT, K. H., Principles of Projectile Design for Penetration - Compound Conical-Nosed Tungsten Carbide Cores, Eleventh Partial Report, Watertown Arsenal Laboratories, WAL 762/231-11 (C), 25 October 1955.*

[3] *MASCIANICA, F. S., and RIFFIN, P. V., Principles of Armor Protection, Fifth Partial Report, Watertown Arsenal Laboratories, WAL 710/609-4 (C), 31 May 1956.*

TABLE I (U)

CHEMICAL ANALYSIS OF COMPOSITE ARMOR
(Weight %)

STEEL ARMOR

Element	C	Mn	Si	S	P	Ni	Cr	Mo
	0.27	1.70	0.18	0.017	0.019	Trace	0.02	0.465

SILVER SOLDER*

Element	Ag	Cu	Zn	Cd	Ni
	50.0	15.5	15.5	16.0	3.0

**This is manufacturer's advertised composition.*

TABLE II (U)

DETAILS OF BALLISTIC TESTS CONDUCTED WITH WC AND TiC COMPOSITE ARMOR

Projectile	Thickness (inch) Platelets	Thickness (inch) Steel Armor	Areal Density (PSF) Platelets	Areal Density (PSF) Steel Armor	Total Areal Density (PSF)	Equivalent Steel Thickness (inch)	Obliquity (degrees)
TUNGSTEN CARBIDE							
Cal. .40 AP T33	1/16	0.284	4.80	11.52	16.32	0.400	30
"	1/16	0.382	4.80	15.60	20.40	0.500	30
"	1/8	0.364	9.60	14.88	24.48	0.600	30
"	1/8	0.465	9.60	18.96	28.56	0.700	30
"	1/16	0.284	4.80	11.52	20.40*	0.500	45
"	1/16	0.382	4.80	15.60	24.48*	0.600	45
"	1/8	0.364	9.60	14.88	28.56*	0.700	45
"	1/8	0.465	9.60	18.96	32.64*	0.800	45
"	1/16	0.284	4.80	11.52	16.32	0.400	60
"	1/16	0.382	4.80	15.60	20.40	0.500	60
"	1/8	0.364	9.60	14.86	24.46	0.600	60
Cal. .50 AP M2	1/16	0.382	4.80	15.60	24.48*	0.600	30
"	1/16	0.382	4.80	15.60	24.48*	0.600	45
Cal. .40 #19B WC Cores	1/8	0.765	9.60	31.20	44.88*	1.100	30
"	1/8	0.765	9.60	31.20	44.88*	1.100	45
"	1/8	0.765	9.60	31.20	44.83*	1.100	60
TITANIUM CARBIDE							
Cal. .40 AP T33	1/8	0.408	3.77	16.63	24.48*	0.600	0
"	1/8	0.508	3.77	20.71	28.56*	0.700	0
"	1/16	0.352	1.89	14.43	20.40*	0.500	30
"	1/8	0.408	3.77	16.63	24.48*	0.600	30
"	1/8	0.508	3.77	20.71	28.56*	0.700	30
"	1/4	0.520	7.54	21.02	32.64*	0.800	30
"	1/4	0.615	7.54	25.10	36.72*	0.900	30
"	1/8	0.408	3.77	16.63	24.48*	0.500	45
"	1/8	0.508	3.77	20.71	28.56*	0.700	45
"	1/16	0.352	1.89	14.43	20.40*	0.500	60
"	1/8	0.408	3.77	16.63	24.48*	0.600	60
"	1/8	0.508	3.77	20.71	28.56*	0.700	60
20MM FSP	1/16	0.164	1.89	6.27	12.24*	0.300	30
"	1/16	0.352	1.89	14.43	20.40*	0.500	30
"	1/16	0.164	1.89	6.27	12.24*	0.300	60
"	1/16	0.352	1.89	14.43	20.40*	0.500	60

**A 0.100"-thick Hadfield-Manganese sheet was used.*

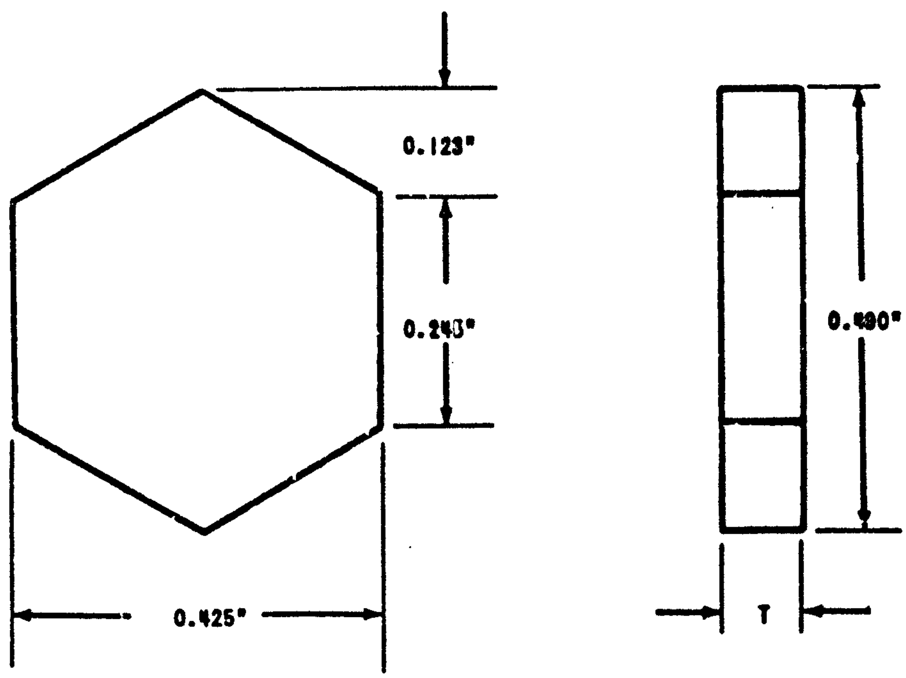
TABLE III (C)

COMPARATIVE BALLISTIC DATA OF WC AND TiC COMPOSITE ARMOR AND ROLLED HOMOGENEOUS STEEL ARMOR (U)

Projectile	Thickness (inch) Equivalent Steel	Thickness (inch) Facing	Thickness (inch) Steel Armor	Obliquity (degrees)	Protection (V_{50}) Ballistic Limit: Equivalent Steel (FPS) (Ref. 3)	Protection (V_{50}) Ballistic Limit: Composite (FPS)	% Superiority of Composite Armor Over Steel
TUNGSTEN CARBIDE FACING							
Cal. .40 AP T33	0.400	1/16	0.284	30	2390	2495**	4.4
"	0.500	1/16	0.382	30	2935	3002**	2.3
"	0.600	1/8	0.364	30	3490	3320**	-0.8
"	0.700	1/8	0.465	30	4020	4060**	1.0
"	0.500	1/16	0.284	45	3350	3217	-4.0
"	0.600	1/16	0.382	45	4030	3299	-18.1
"	0.700	1/8	0.364	45	4640	3673	-20.8
"	0.800	1/8	0.465	45	5440	4215	-22.5
"	0.400	1/16	0.284	60	3490	3595**	3.0
"	0.500	1/16	0.382	60	4350	4005**	-7.9
"	0.600	1/8	0.364	60	5110	5004**	-2.1
"	0.750*	--	0.750	30	4800**	--	--
"	1.224*	1/4	0.750	30	--	4800 HP**	--
Cal. .50 AP M2	0.500	1/16	0.382	30	2860	1488	-48.0
"	0.600	1/16	0.382	45	3400	2100 HP	>-38.4
Cal. .40 H19B WC Cores	1.100	1/8	0.765	30	2940	2565	-12.8
"	1.100	1/8	0.765	45	3160	3148	-0.4
"	1.100	1/8	0.765	60	5115	4455 HP	>-12.9
TITANIUM CARBIDE FACING							
Cal. .40 AP T33	0.600	1/8	0.408	0	2400	2694	12.2
"	0.700	1/8	0.508	0	2700	3576	32.4
"	0.500	1/16	0.352	30	2935	2569	-12.5
"	0.600	1/8	0.408	30	3490	3656	4.8
"	0.700	1/8	0.508	30	4020	3620	-9.9
"	0.800	1/4	0.520	30	4810	5008	4.1
"	0.900	1/4	0.615	30	5600	4780 LC	--
"	0.600	1/8	0.408	45	4030	4199	4.2
"	0.700	1/8	0.508	45	4640	4127	-11.2
"	0.500	1/16	0.352	60	4350	4028	-7.4
"	0.600	1/8	0.408	60	5110	5215	2.1
"	0.700	1/8	0.508	60	5770	5790 HP	>0.4
"	0.750*	--	0.750	30	4800	--	--
"	0.935*	1/4	0.750	30	--	4800 HP	--
20MM FSP	0.300	1/16	0.154	30	1940	1640	-15.5
"	0.500	1/16	0.352	30	2973	2568	-13.6
"	0.300	1/16	0.151	60	2840	1976	-30.4
"	0.500	1/16	0.352	60	4220	4410 HP	>4.5
Cal. .40 WC Cores	1.000*	--	1.000	30	2650**	--	--
"	1.185*	1/4	1.000	30	--	>3850**	--

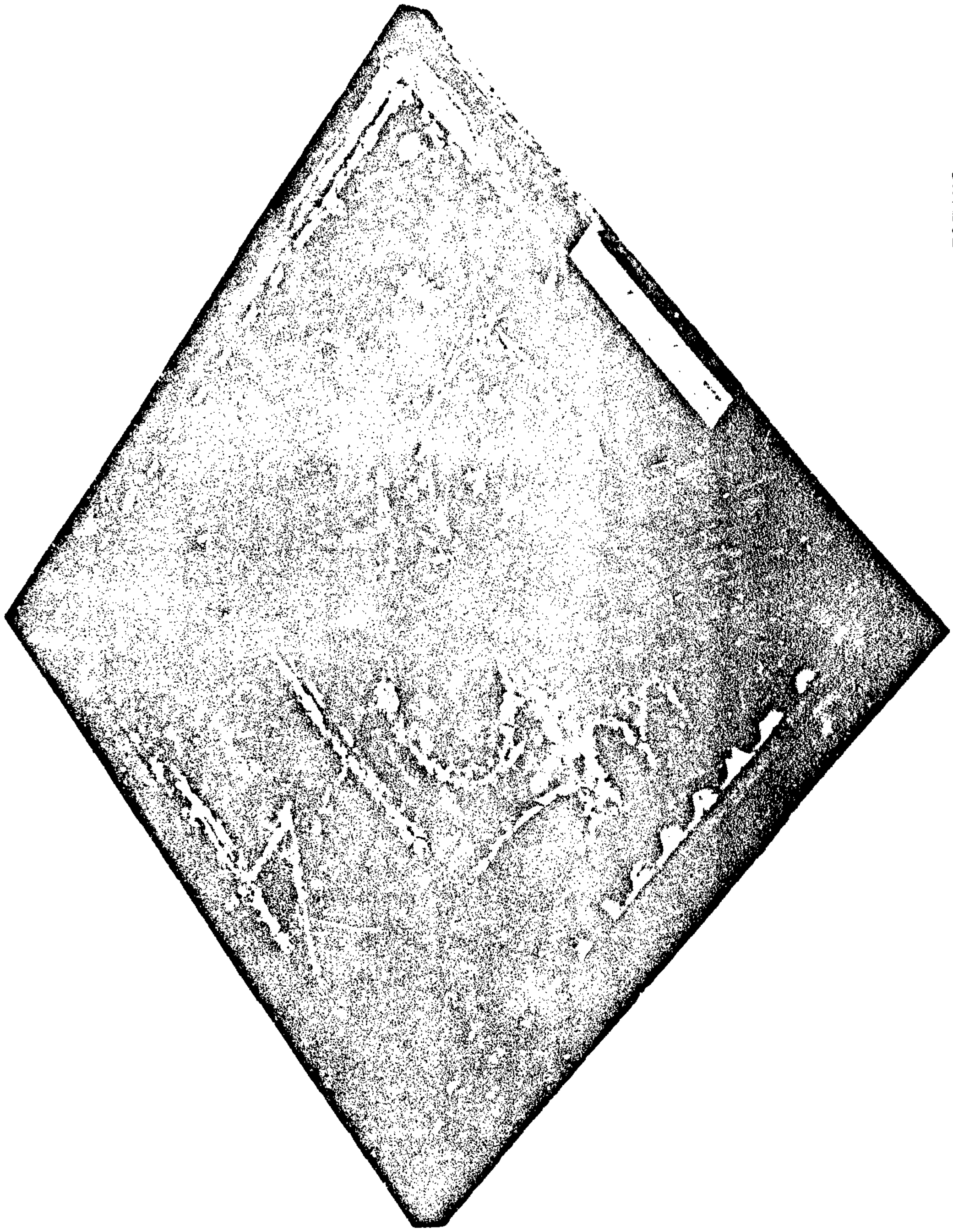
NOTES: HP - Highest partial penetration
LC - Lowest complete penetration

*Kennametal Corporation data.
**No Hadfield-Manganese sheet used.



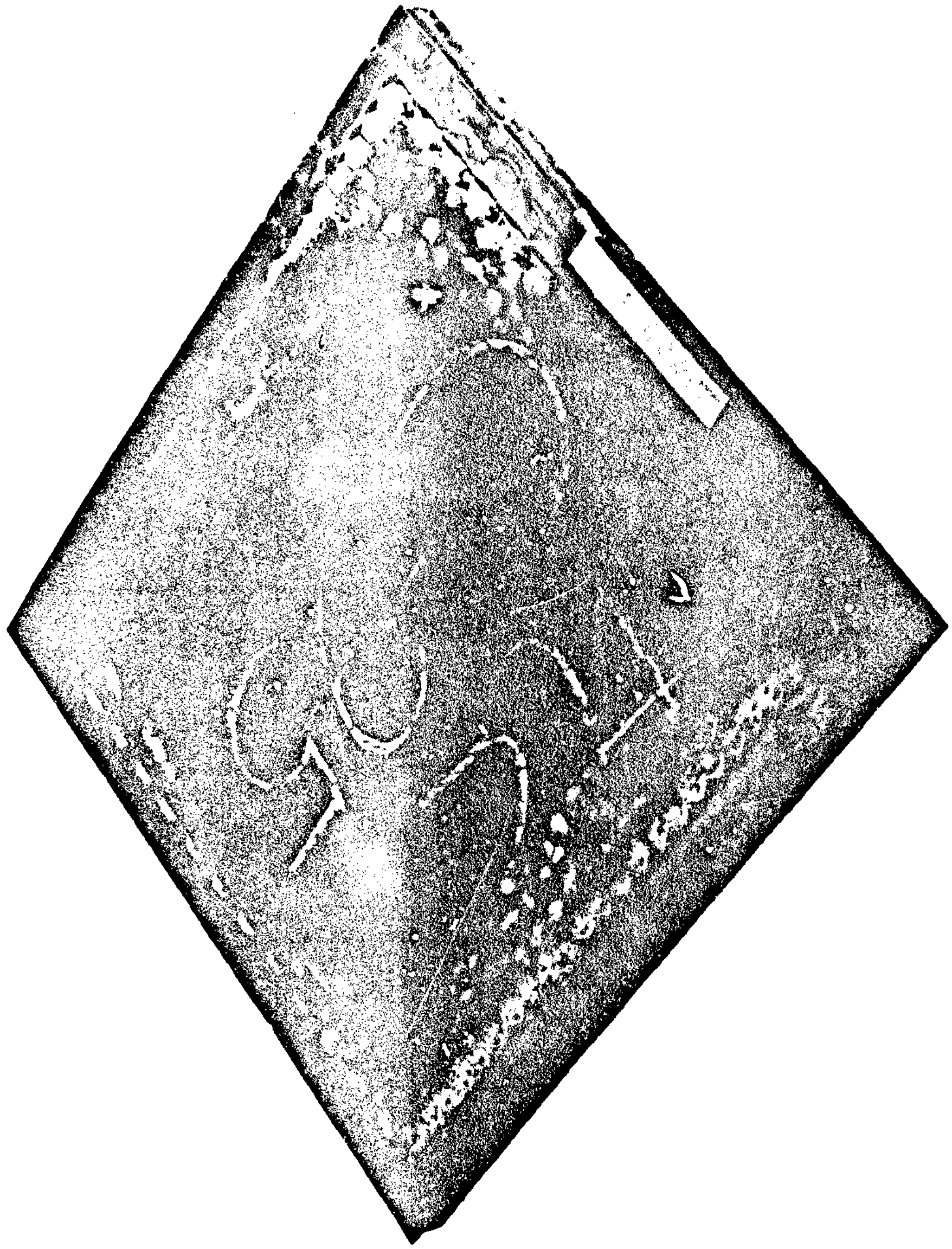
DIMENSION OF FACING USED FOR FABRICATION OF COMPOSITE ARMOR

FIGURE I



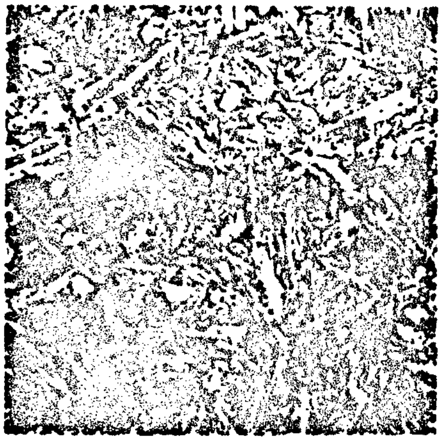
TUNGSTEN CARBIDE COMPOSITE ARMOR PLATE PRIOR TO BALLISTIC TESTING

FIGURE 2



TITANIUM CARBIDE COMPOSITE ARMOR PLATE PRIOR TO BALLISTIC TESTING

FIGURE 3



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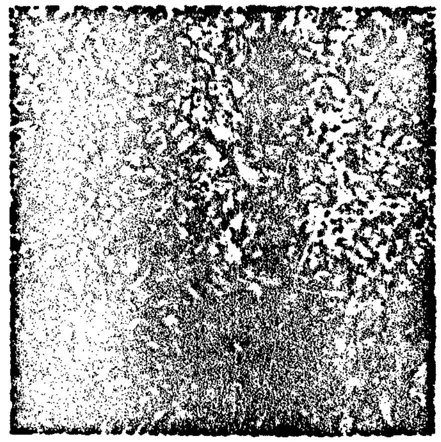

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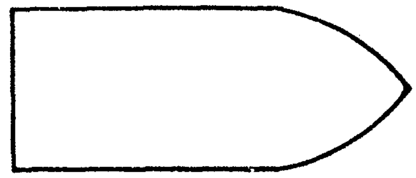
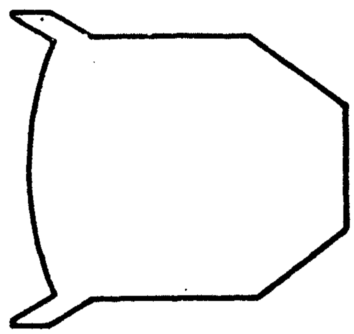
ETCHANT 4% PICRAL + 1 DROP HCl

PHOTOMICROGRAPHS OF STEEL ARMOR PLATE AFTER BRAZING

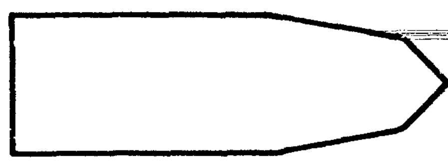
FIGURE 4



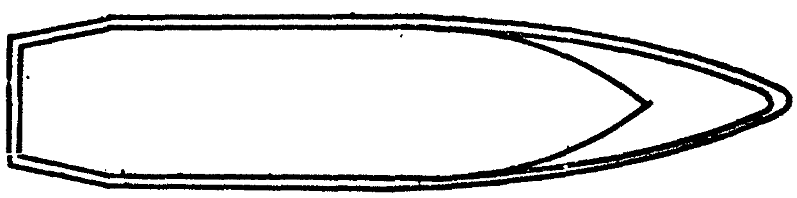
CALIBER 0.40 AP T32



20MM FRAGMENT SIMULATING PROJECTILE



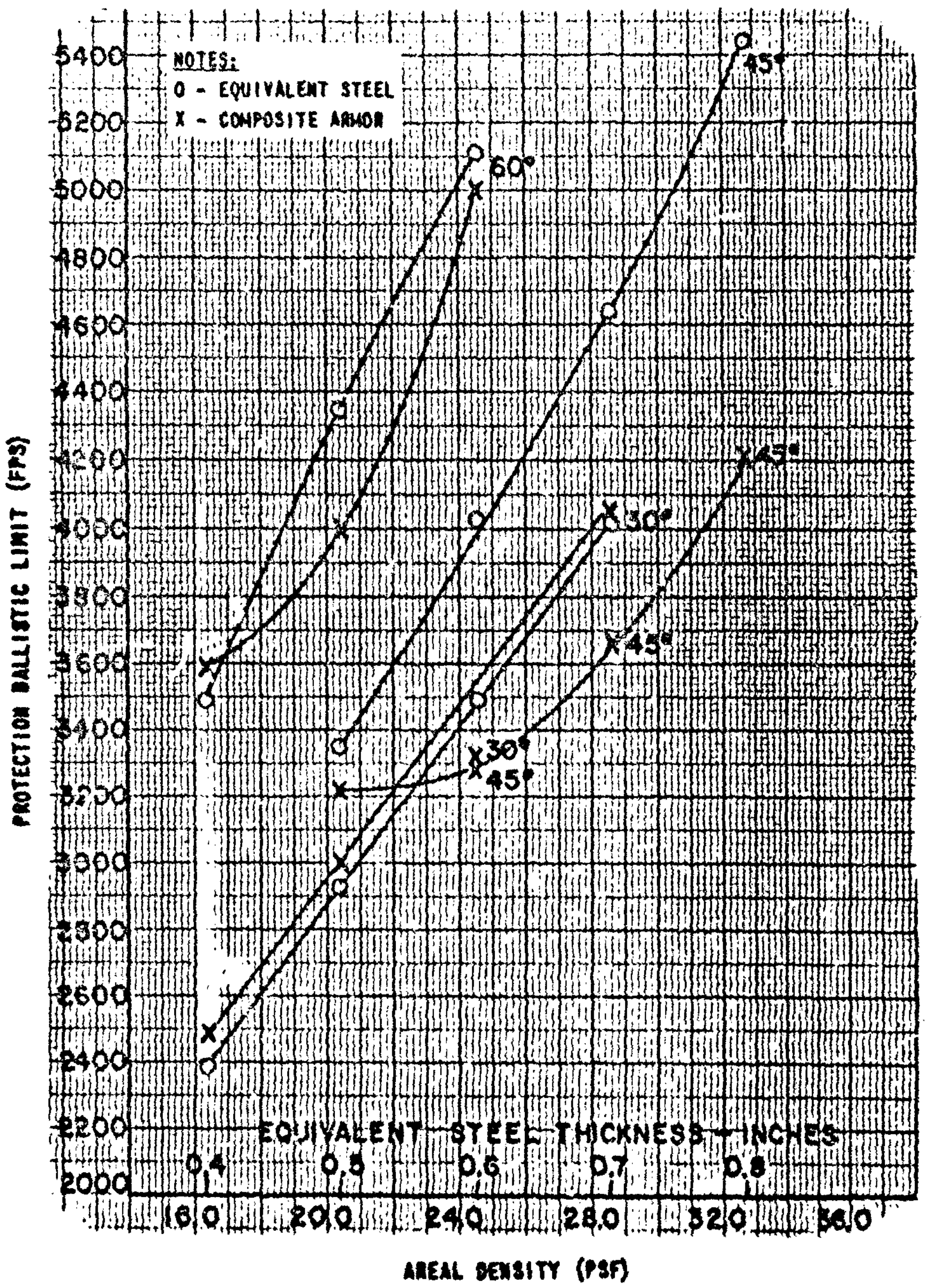
CALIBER 0.40 M188 WC CORE



CALIBER 0.50 AP M2

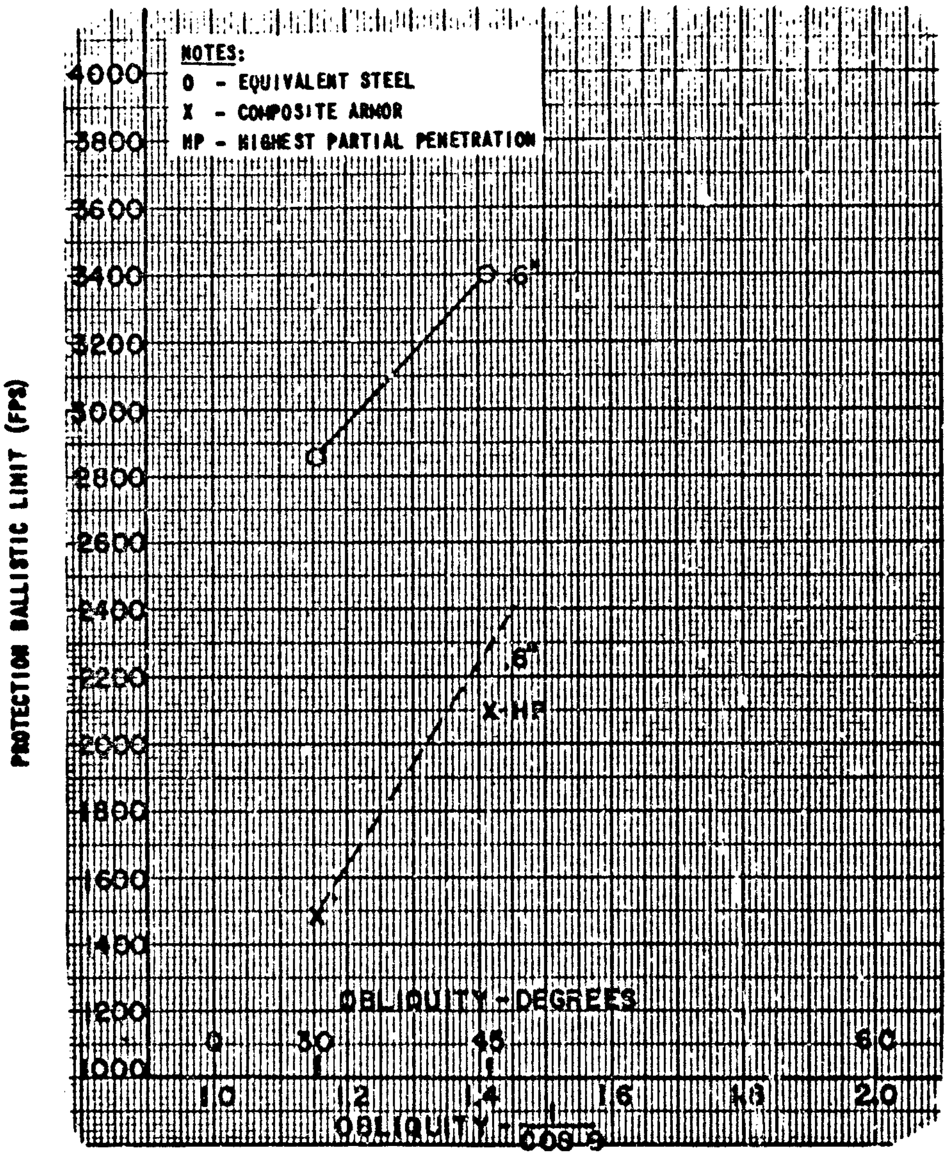
PROJECTILES USED TO DETERMINE BALLISTIC PERFORMANCE
OF WC AND TiC COMPOSITE ARMOR

FIGURE 5



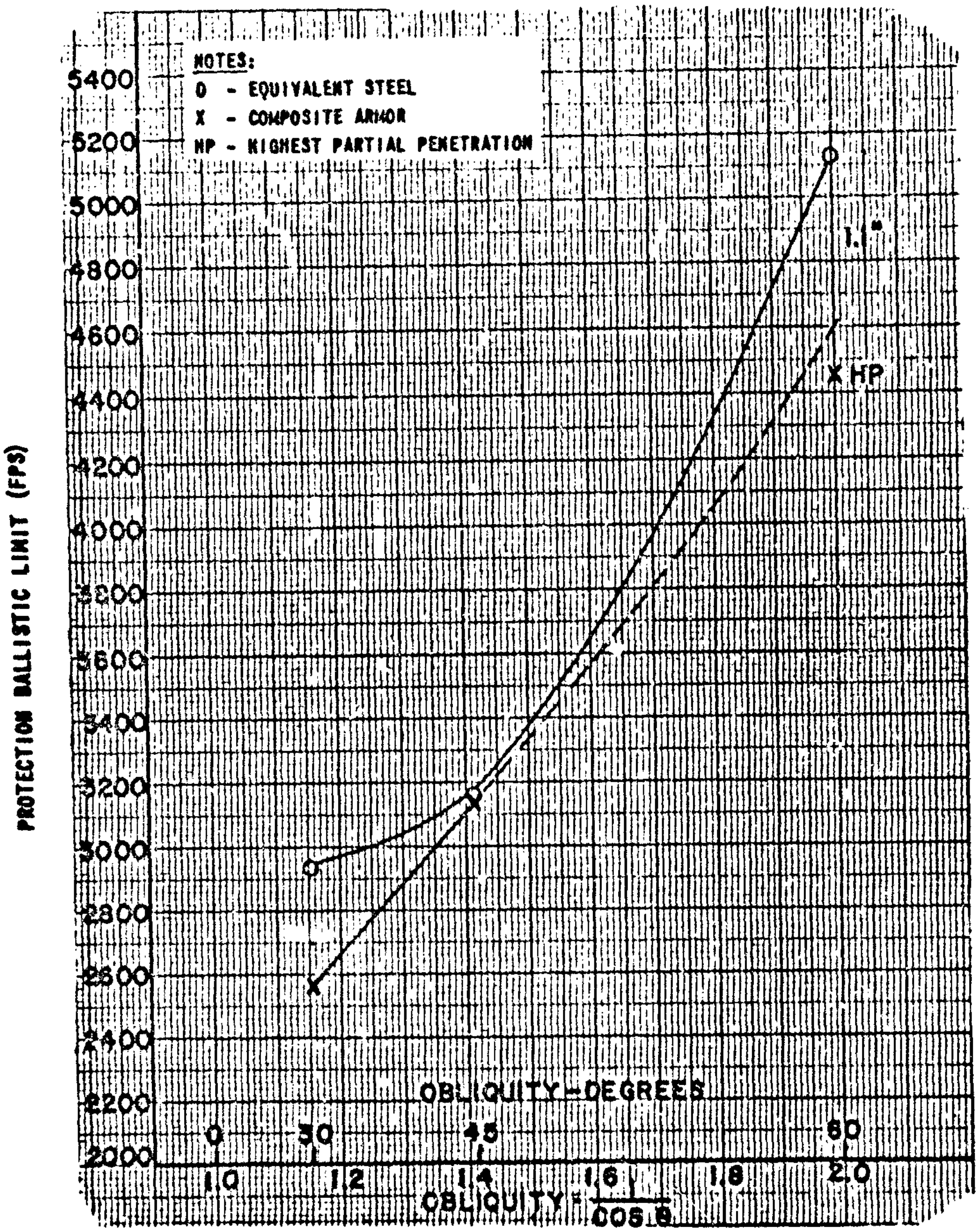
COMPARATIVE BALLISTIC PERFORMANCE OF WC COMPOSITE ARMOR WHEN ATTACKED BY CALIBER 0.40 AP T33 SCALE MODEL PROJECTILES

FIGURE 6



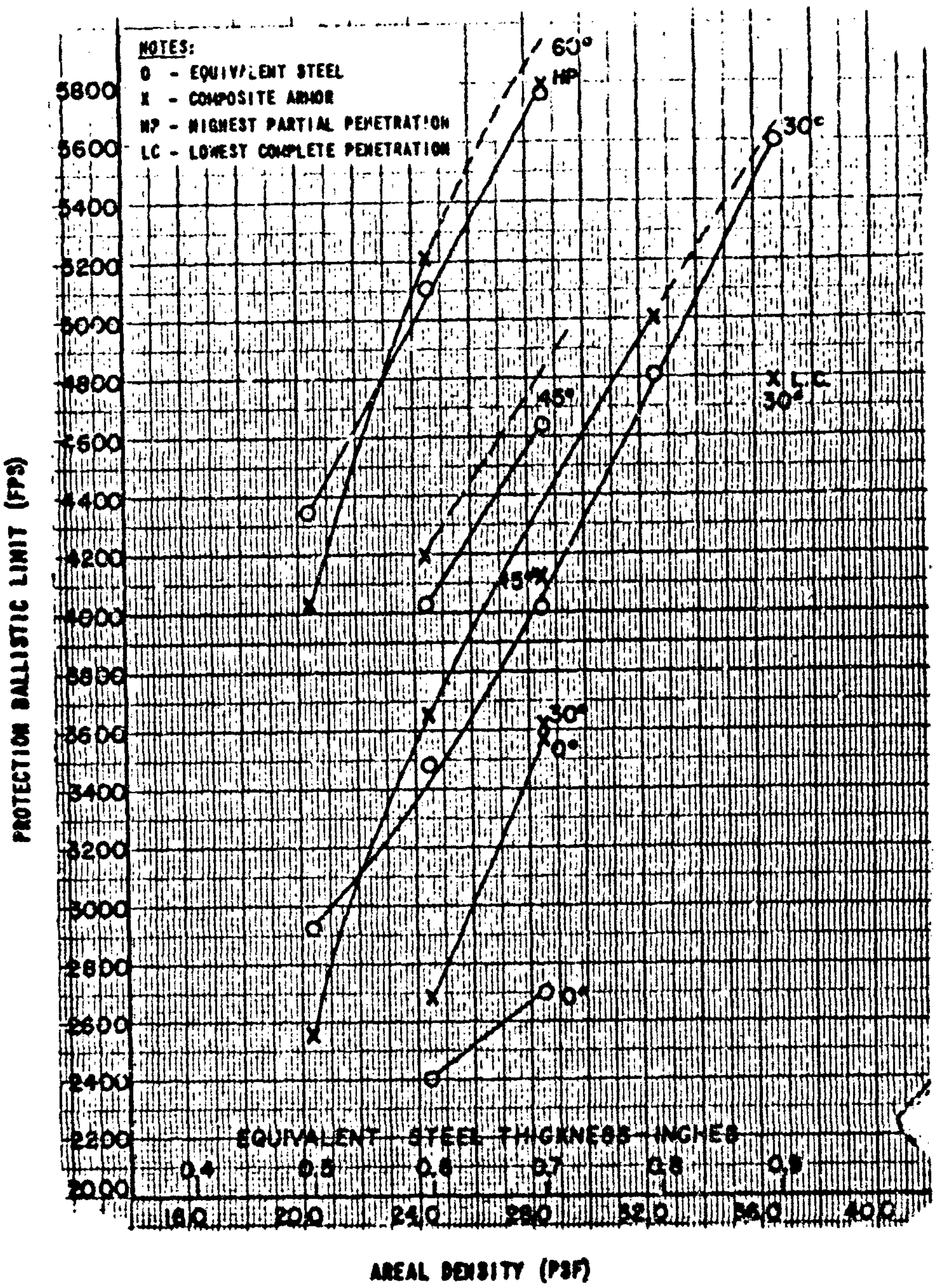
COMPARATIVE BALLISTIC PERFORMANCE OF WC COMPOSITE ARMOR WHEN ATTACKED BY CALIBER 0.50 AP M2 PROJECTILES

FIGURE 7



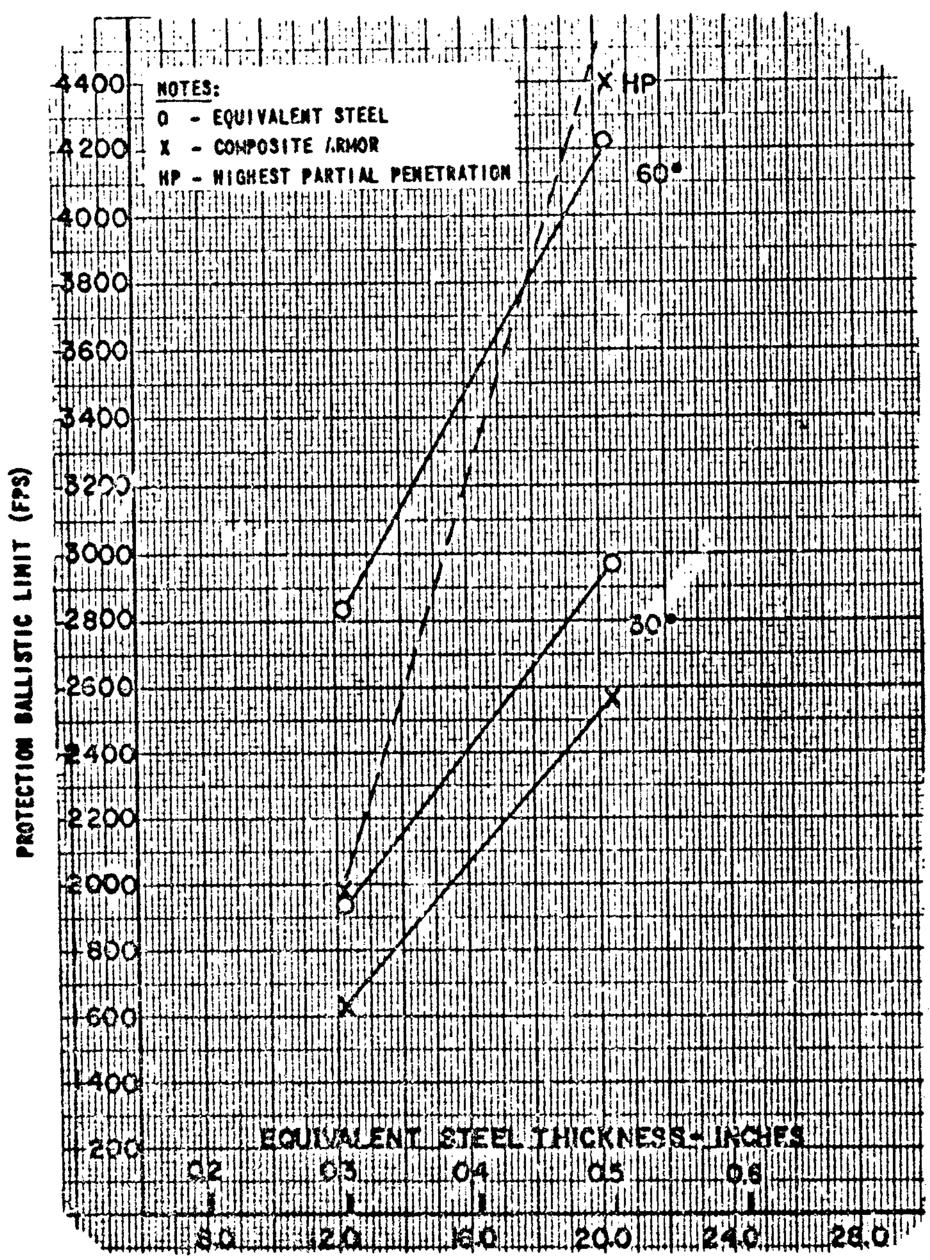
COMPARATIVE BALLISTIC PERFORMANCE OF WC COMPOSITE ARMOR WHEN ATTACKED BY CALIBER 0.40 H19B WC CORES

FIGURE 8



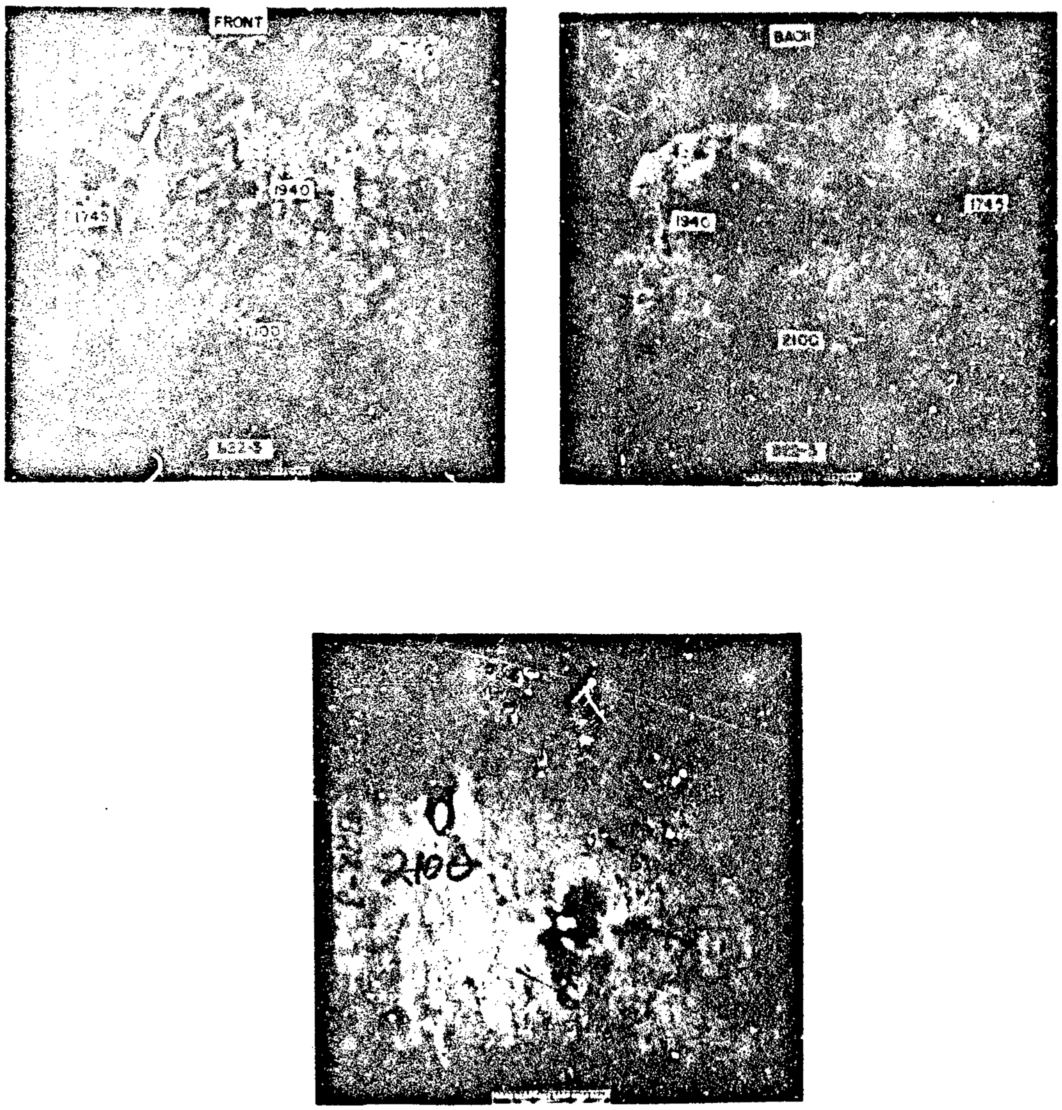
COMPARATIVE BALLISTIC PERFORMANCE OF TIC ARMOR WHEN ATTACKED BY CALIBER 0.40 AP T33 PROJECTILES

FIGURE 9



COMPARATIVE BALLISTIC PERFORMANCE OF TIC COMPOSITE ARMOR WHEN ATTACKED 20MM FRAGMENT SIMULATING PROJECTILES

FIGURE 10



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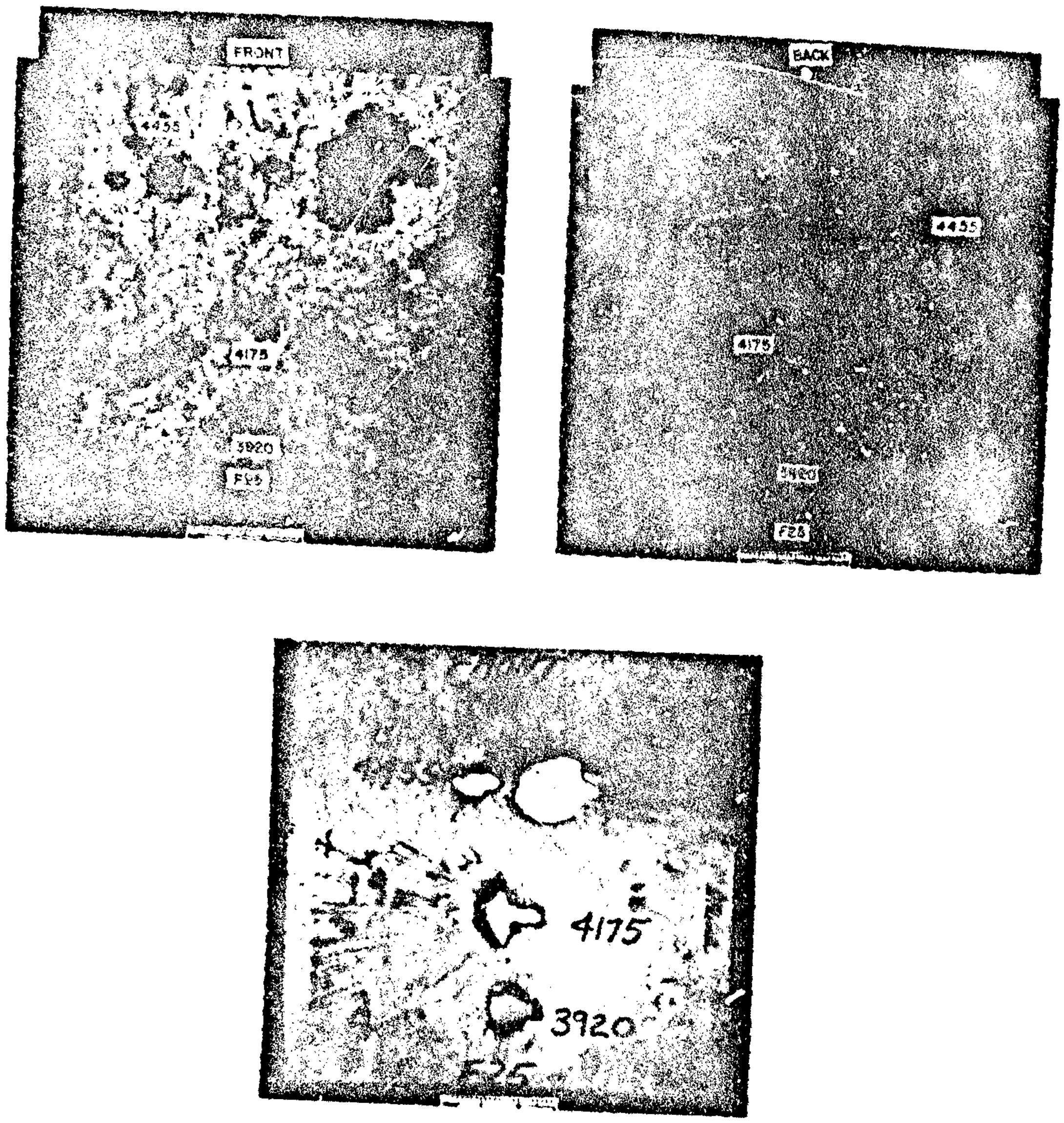
TUNGSTEN CARBIDE COMPOSITE ARMOR PLATE ATTACKED BY CALIBER 0.50
AP M2 PROJECTILES AT 45° OBLIQUITY

FIGURE 11



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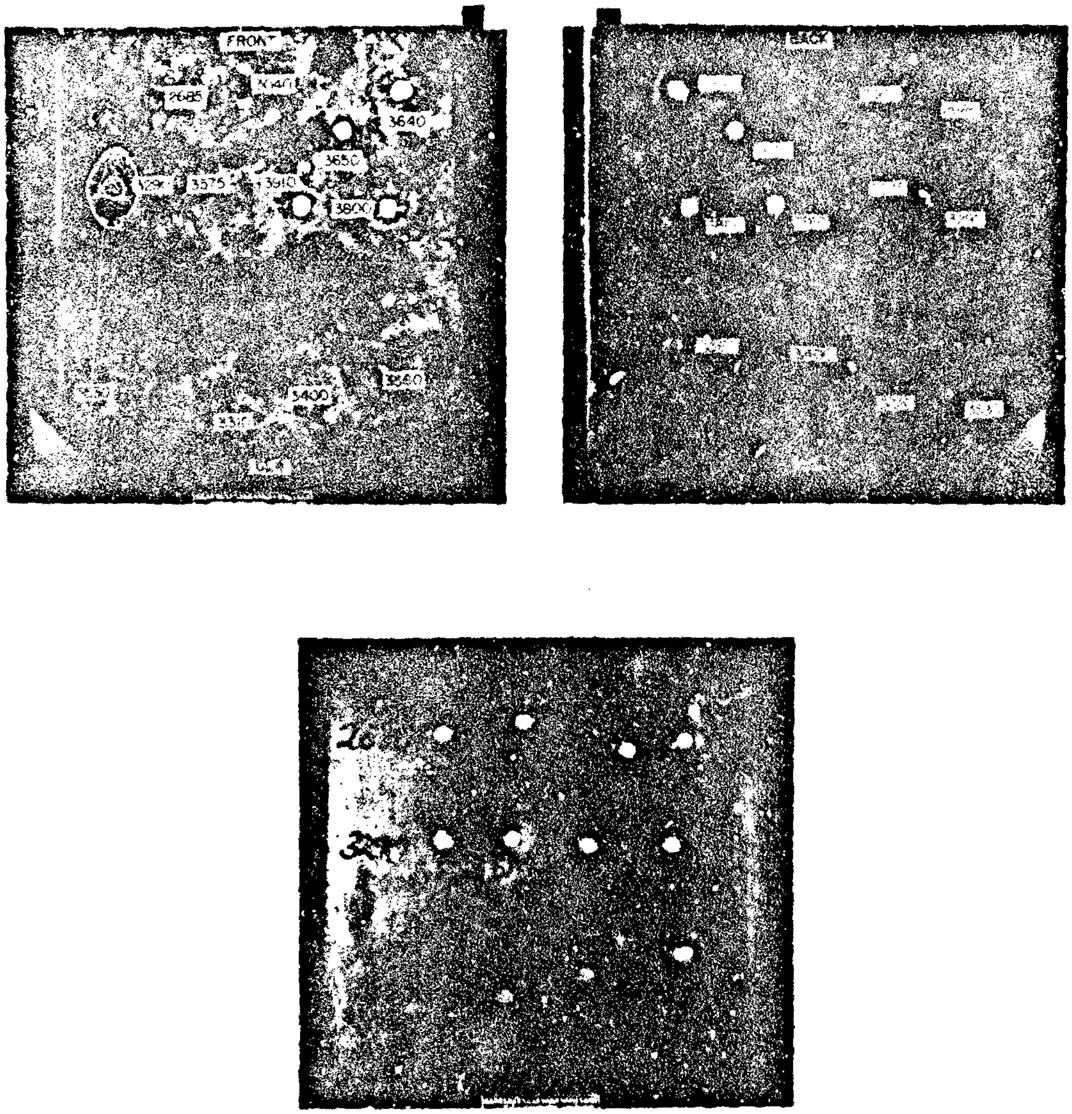
TUNGSTEN CARBIDE COMPOSITE ARMOR PLATE ATTACKED BY CALIBER 0.40
H19B WC CORES AT 60° OBLIQUITY

FIGURE 12



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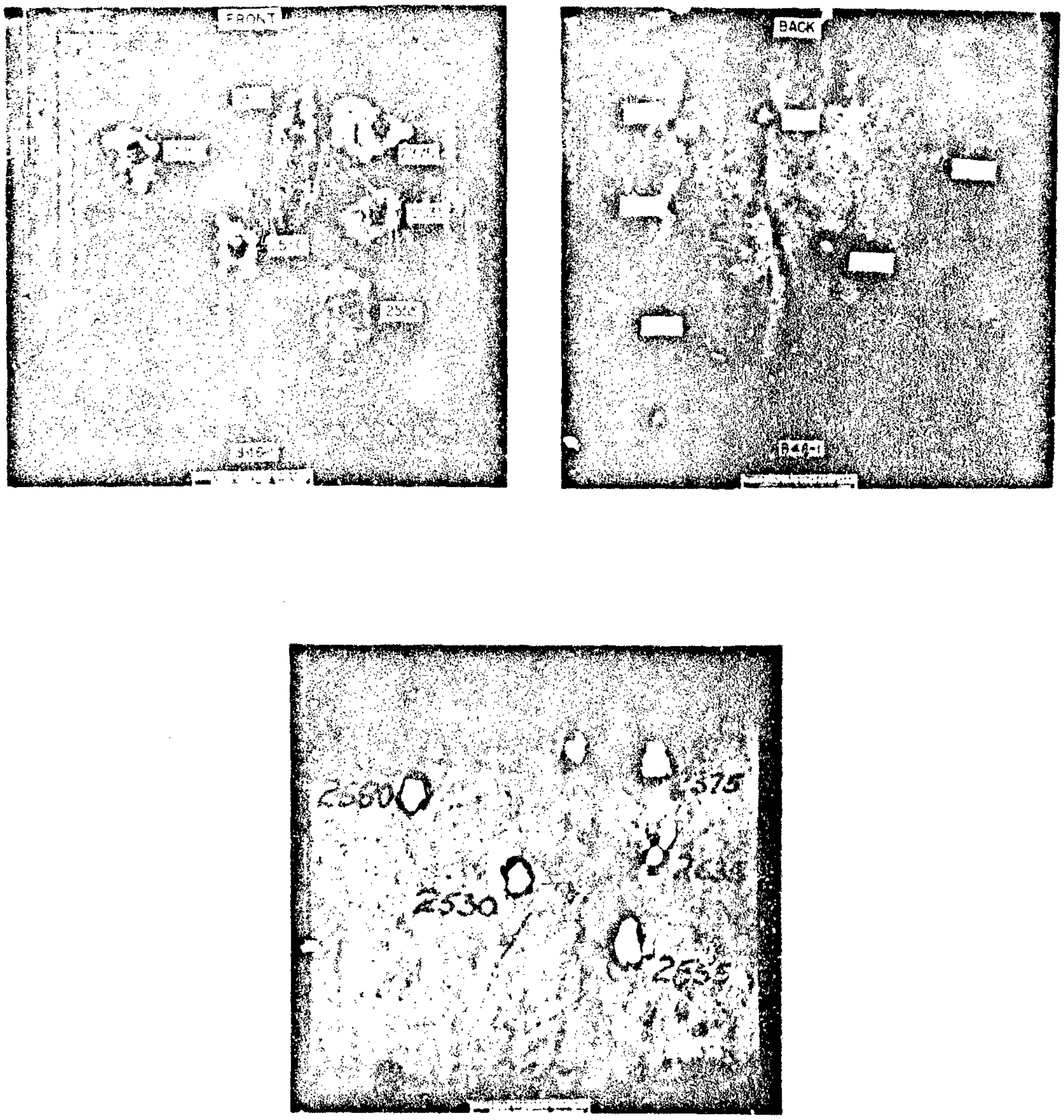
TITANIUM CARBIDE COMPOSITE ARMOR PLATE ATTACKED BY CALIBER 0.40 AP T33 PROJECTILES AT 0° OBLIQUITY

FIGURE 13



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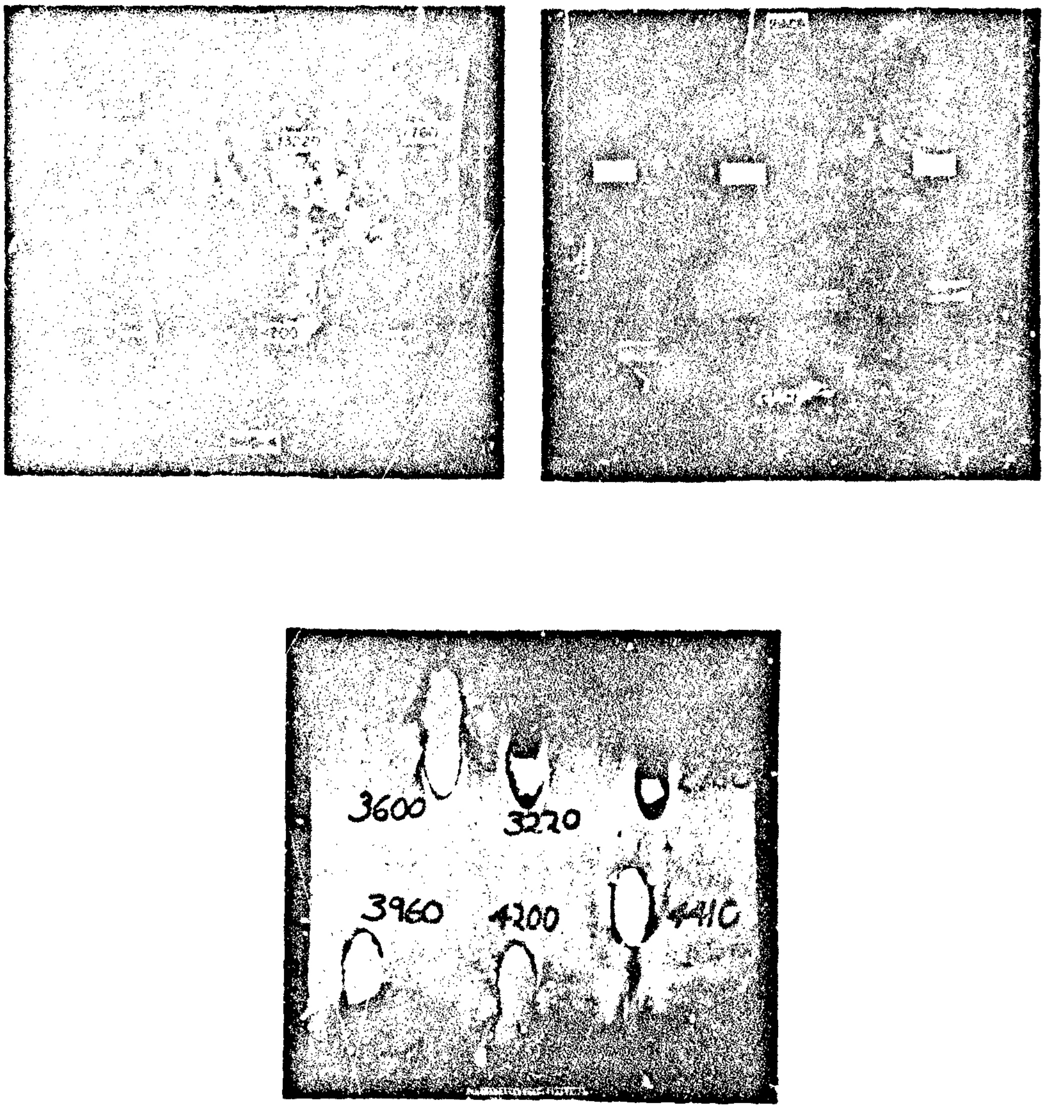
TITANIUM CARBIDE COMPOSITE ARMOR PLATE ATTACKED BY CALIBER 0.40 AP T33 PROJECTILES AT 30° OBLIQUITY

FIGURE 14



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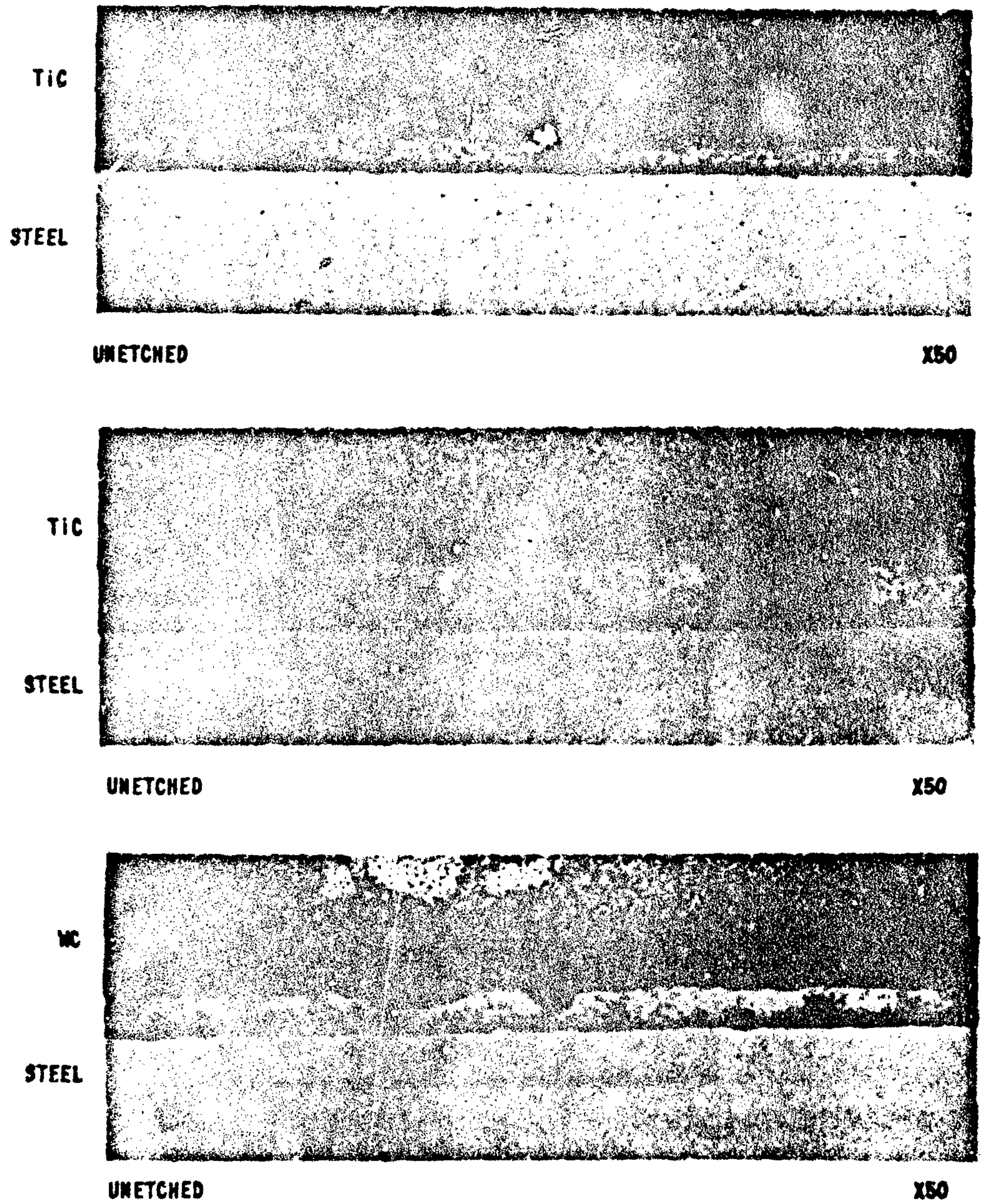
TITANIUM CARBIDE COMPOSITE ARMOR PLATE ATTACKED BY 20MM FRAGMENT SIMULATING PROJECTILES AT 60° OBLIQUITY

FIGURE 15



PHOTOMICROGRAPHS OF BRAZED JOINTS

FIGURE 16

APPENDIX A

ROUND BY ROUND BALLISTIC DATA FOR WC AND TiC COMPOSITE ARMOR

TUNGSTEN CARBIDE

Projectile	Equivalent Steel Thickness (inch)	Obliquity (degrees)	Velocity (fps)	Scabbing Dimension (Inches) Length	Width
Caliber .40 AP T39	0.400	30	2510 CP	1½	2
			2510 CP	2	1½
			2500 PP	2½	3
			2400 PP	2½	3
			B. L. -2495		
"	0.500	30	3085 CP	-	-
			2955 CP	-	-
			3030 PP	-	-
			2935 PP	-	-
			B.L. - 3082		
"	0.600	30	3390 CP	3	3
			3345 CP	4	4½
			3235 PP	-	-
			3270 PP	2½	4
			B.L. - 3320		
"	0.700	30	4120 CP	5	4
			4140 CP	5½	4
			4005 PP	6	4
			3965 PP	-	-
			B.L. - 4060		
"	0.500	45	3120 CP	-	-
			3315 PP	-	-
			B.L. - 3117		
"	0.600	45	3330 CP	-	-
			3315 CP	-	-
			3310 PP	-	-
			3240 PP	-	-
			B.L. - 3299		
"	0.700	45	3670 CP	1	1
			3690 CP	3	5
			3740 PP	-	-
			3600 PP	-	-
			B.L. - 3673		
"	0.800	45	4260 CP	-	-
			4180 PP	-	-
			B.L. - 4215		
"	0.400	60	3595 CP	2½	3
			3555 CP	2	1½
			3550 PP	2	2
			3540 PP	2½	2
			B.L. - 3606		
"	0.400	60	4000 CP	3	3
			4005 PP	-	-
			B.L. - 4006		

TUNGSTEN CARBIDE (Cont'd)

Projectile	Equivalent Steel Thickness (inch)	Obliquity (degrees)	Velocity (fps)	Scabbing Dimension (inches)	
				Length	Width
Caliber .40 AP T33	0.600	60	5020 CP	6	6
			5070 CP	-	-
			4965 PP	-	-
			4940 PP	7	7
				B.L. - 5004	
Caliber .50 AP M2	0.600	30	1455 CP	4	3
			1520 PP	4	4
				B.L. - 1488	
"	0.600	45	2100 PP	-	-
Caliber .40 H19B WC Cores	1.100	30	2645 CP	7	6
			2485 PP	-	-
				B.L. - 2565	
"	1.100	45	3185 CP	3	3
			3110 PP	-	-
				B.L. - 3148	
"	1.100	60	4455 PP	-	-

TITANIUM CARBIDE

Projectile	Equivalent Steel Thickness (inch)	Obliquity (degrees)	Velocity (fps)	Length	Width
Caliber .40 AP T33	0.600	0	2735 CP	-	-
			2640 CP	2	2½
			2735 PP	1½	1½
			2666 PP	2½	2
				B.L. - 2694	
"	0.700	0	3630 CP	2	2
			3640 CP	2	2½
			3675 PP	1	1
			3500 PP	-	-
				B.L. - 3576	
"	0.500	30	2630 CP	-	-
			2610 CP	1½	2
			2580 PP	-	-
			2555 PP	1	1½
				B.L. - 2569	
"	0.600	30	3735 CP	2	2
			3580 PP	2	2
				B.L. - 3658	
"	0.700	30	3630 CP	-	-
			3610 PP	-	-
				B.L. - 3620	
"	[illegible]	30	5045 CP	6	5
			4970 PP	5	5
				B.L. - 5008	
"	0.900	30	4780 LC	-	-

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TITANIUM CARBIDE (Cont'd)

Projectile	Equivalent Steel Thickness (inch)	Obliquity (degrees)	Velocity (fps)	Scabbing Dimension (inches) Length	Width
Caliber .40 AP T33	0.600	45	4215 CP	3	3
			4270 CP	-	-
			4190 PP	3	4
			4120 PP	4	6
				B. L. - 4190	
"	0.700	45	4165 CP	2	2
			4210 CP	2½	2
			4075 PP	2	1½
			4060 PP	2½	3
				B. L. - 4137	
"	0.500	60	4060 CP	-	-
			3995 PP	2½	3
				B. L. - 4028	
"	0.600	60	5315 CP	4	5
			5115 PP	-	-
				B. L. - 5215	
"	0.700	60	5790 HP	-	-
20MM FSP	0.300	30	1650 CP	6	5½
			1630 PP	5½	3½
				B. L. - 1640	
"	0.500	30	2555 CP	4	3
			2580 PP	-	-
				B. L. - 2568	
"	0.300	60	2040 CP	-	-
			1915 PP	-	-
				B. L. - 1978	
"	0.400	60	4410 CP	-	-

NOTES:
1. *CP - Complete Penetration*
2. *PP - Partial Penetration*
3. *HP - Highest Partial Penetration*
4. *LC - Lowest Complete Penetration*

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Report No. WAL TR 161.3/1 (C), Dec 1960, 31 pp - tables - illus - appendix - OMS Code 5010.11.8090051 Confidential Report

(U) Ballistic testing was conducted to determine the comparative performance of WC-steel and TiC-steel composite armor when attacked by cal. .40 H19B WC cores, cal. .50 AP M2 projectiles, 20MM fragment simulating projectiles, and cal. .40 AP T33 scale model projectiles, at various obliquities. The composite armor was compared to rolled homogeneous steel armor on an areal density basis.

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