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Final Report on AN ANALYTICAL STUDY OF DATA ON ARMOR PENETRATION BY TANK-FIRED, KINETIC ENERGY PROJECTILES

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FINAL REPORT

on

AN ANALYTICAL STUDY OF DATA ON ARMOR PENETRATION BY TANK-FIRED, KINETIC ENERGY PROJECTILES

Ord Project No. TB3-1224B
D/A Project No. 5B0304004

to

ORDNANCE DEPARTMENT
RESEARCH AND DEVELOPMENT DIVISION
DEPARTMENT OF THE ARMY

31 May 1958

by

J. C. Bell and L. E. Hulbert

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AN ANALYTICAL STUDY OF DATA ON ARMOR PENETRATION BY TANK-FIRED, KINETIC ENERGY PROJECTILES

by

J. C. Bell and L. E. Hulbert

SUMMARY

This report ~~describes a survey of Aberdeen Proving Ground~~ data on penetration of homogeneous armor by kinetic energy projectiles. The projectiles were of the types that have been or might be fired from tanks, with calibers ranging from 37 mm to 155 mm. The data were collected for individual rounds and pertinent information for each round was punched on IBM cards, one card to a round. The data processing began only when all similar rounds fired at similar targets had been assembled. Insofar as possible, ballistic limits for each projectile-target situation were computed by carefully designed statistical procedures (~~programmed for the IBM Type 650 Magnetic Drum Data Processing Machine~~) with which measures of the precision of each limit could be stated. Through a careful and continuous study of the data, several observations were made concerning factors which affect the dependability of results from penetration tests. Finally, the results of the survey, based on over 20,000 rounds of over 50 kinds of projectiles, are compiled into a large table. This table should furnish a convenient reference for penetration data, and should serve as a step toward further correlation and condensation of the data.

BACKGROUND

The conventional means for defeating tank armor has long been projectiles which penetrate the armor by virtue of their kinetic energy at the instant of impact. Many studies, mostly empirical but some theoretical, have been made to find how fast a given projectile must be traveling in order to penetrate a given piece of armor. The theoretical work is difficult, so simplifications must be introduced, and these generally prevent the results from having broad applicability. On the other hand, experiments with regular projectiles are expensive, so many early experiments were conducted with relatively limited test conditions.

One way to get fairly broad empirical results economically is to restrict attention to small caliber projectiles. A widely quoted formula from the National Physical Laboratory* was based on experiments with projectiles from 0.296 in. to 1.565 in. in diameter against plates 5 to 80 mm thick, having Brinell hardness 250 to 450 kg/mm^2. Later work permitted the formula to be amended to include the influence of obliquity of the line of fire with respect to the target. As the formula was proposed it predicted velocities required for intact projectiles to achieve penetrations complete in the Navy sense, that is, with at least half the weight of the projectile passing completely through the plate. In order to broaden the usefulness of the formula, means were developed in Project Thor** for adapting the formula to broken projectiles, and for predicting penetrations complete in the Army sense, that is, where light shows through the hole when the projectile is removed. Still this work referred to small projectiles, ranging in diameter from 0.30 in. to 37 mm, and most of the target plates had thicknesses of an inch or less. Data for the Project Thor correlation were drawn largely from a single Aberdeen Proving Ground Report***.

The NPL formula, as quoted in the Project Thor Report, is:

$$\frac{mV_L^2}{d^3} = \left(43.4\sqrt{B}\,\frac{e}{d}\sec\frac{3[illegible]}{2} + 929 - \frac{11,900}{65 - [illegible]} - \frac{54,000}{B_0 - B}\right)^2 .$$

where

V_L = ballistic limit in ft/sec

d = diameter of the projectile core in inches

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*Sopwith, D. G., "The Optimum Hardness of Homogeneous Armor for Resistance to Perforation at Normal Attack by Projectiles of Different Sizes", Fourth Progress Report on Effect of Scale in Armor Penetration, A. P. P. Coordinating Subcommittee Paper No. [illegible], N. P. L. Engineering Division, Britain, (September 1944), Confidential. Cf. National Defense Research Committee, "Effects of Impact and Explosion", Summary Technical Report of Division 2, N. D. R. C., Vol. 1 (1946), p. [illegible], Confidential.

**Johns Hopkins University, "A Suggested Technique for Predicting the Performance of Armor Piercing Projectiles [illegible] on Rolled Homogeneous Armor", Project Thor Technical Report No. 14 (September 1950), Confidential.

***Aberdeen Proving Ground, "Effects of Hardness, Obliquity, and Plate Thickness on the Ballistic Properties of Rolled Homogeneous Armor when Subjected to Attack by Various Projectiles", AD 111 (July 1948), Restricted.

B = Brinell Hardness Number in kg/mm^2 units

e = thickness of the armor in inches

$$B_o = 500 - 160 \log_{10}\left(\frac{d}{d'}\right)$$

d' = 1.565 in., the diameter of the British 2-pounder shot

θ = angle of attack, measured in degrees off the normal.

The corrections to this formula devised for Project Thor are shown graphically in the same report.

Although the studies mentioned were limited to small caliber projectiles, there are many data referring to full-scale tests with the kinds of projectiles used by tanks, that is, from 37 to 120 mm, and some even larger. The Aberdeen Proving Ground has conducted many experimental programs with such projectiles for various (though often limited) motives. Thus, a moderate amount of firing was done in testing early designs of new projectiles. One substantial program (Project AX 23) tested various steels for a single projectile, the 90 mm AP, T33E7. A long series of related tests (Project 2864) was designed to show the effect of hardness of the plate in withstanding the shot, and since plate obliquity was known to be important, variations were introduced in that too. Fairly recently, a large, more fully organized program (Projects TB4-150M and TB4-10A) was performed for testing the effects of plate hardness, obliquity, and type (whether cast or rolled*), using more modern projectiles. In addition, many other experiments were performed for a variety of special reasons.

Since the voluminous results of these full-scale tests were quite scattered, the Ballistic Research Laboratories undertook to assemble the results into a more concise form. Two reports were published on this subject. The first** was simply a collection of ballistic limits as reported in the many firing records. The second report*** provided an empirical correlation of these limits. The number of ballistic limits considered in the correlation process was 2364, with 1475 for rolled and 889 for cast armor. The projectiles included 11 varieties of AP shot, 9 of APC, and 11 of HVAP. There were, of course, many obliquities and plate thicknesses, chosen to make suitable targets for the projectiles being tested. The results consisted first of a series of graphs showing how the measured ballistic limits varied with the t/d ratio (armor thickness/core diameter) for given projectiles, obliquity, and armor type. Second, a set of predictive curves was fitted in the form:

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*The reports on this project speak also of wrought armor. After some study of the matter it was decided to treat rolled and wrought armor as being essentially the same in the present survey.

**Kilian, B. Roy, An Assembly of Data Concerning the Penetration of Rolled, Wrought and Cast Armor Plate by Kinetic Energy Projectiles [illegible] 37 mm Through 155 mm(U), Ballistic Research Laboratories Technical Note No. [illegible] (May [illegible]), Confidential.

***Kilian, B. Roy, An Empirical Analysis of the Perforation of Rolled and Cast Homogeneous Armor by Conventionally Shaped Kinetic Energy Projectiles of [illegible] 37 mm Thru 155 mm(U), Ballistic Research Laboratories Memorandum Report No. [illegible] (June 1957), Confidential.

$$\text{Ballistic Limit} = K_{\theta}(t/d)^n,$$

where n = 0.85 for AP projectiles, 0.78 for APC, and 0.65 for HVAP; and K_{θ} was tabulated for each combination of armor type (rolled or cast), projectile type (AP, APC, or HVAP) and obliquity. Generally speaking, the correlations were fairly good, but some substantial discrepancies between predicted and measured values remained.

Brief inspection of the ballistic limits tabulated in the BRL collection shows the difficulty of choosing a representative ballistic limit for any test condition, because the tabulated limits for many conditions scatter badly. This is not surprising since the bulk of the limits were found as average velocities of only one complete and one partial penetration, even though more extensive tests usually produce both complete and partial penetrations over a wide range of velocities. The question arises whether there might not be some advantage in combining the penetration data from all similar tests in order to compute an over-all ballistic limit. The resulting limit should be less equivocal, and it may be possible to get confidence limits for it. It should be remembered that this over-all limit can be based on results from many more rounds than contributed to the limits in the BRL collection, since the rounds discarded in getting individual limits can be retained in getting the over-all limit. In addition, results from other kinds of tests, such as shot or plate acceptance, may be considered for use, even though they were never part of a ballistic limit test.

It is the plan of collecting round-by-round results, instead of individual ballistic limits, that forms the basis for the present work. It is recognized, of course, that confusion may result from mechanically combining data from many divergent sources, possibly having systematic discrepancies. However, any such confusion would seem to be a legitimate part of the results, provided all the data are equally relevant.

ASSEMBLING THE DATA

Search for Data

It was known that firing records showing individual rounds were available at several military libraries, but the most promising place to find records for tank-fired projectiles was the Technical Information Branch at the Aberdeen Proving Ground. A total of about 6 man-weeks were spent searching the firing records stored there, selecting those which seemed to contain relevant tests. After the pertinent records were found, the TIB prepared duplicates and sent them to Battelle Memorial Institute. This large work of reproduction (totalling about 14,000 sheets) proved to be of great assistance later in sorting and editing the data. The volume of records found at the TIB seemed to be about as many as could be handled in the present program, so little further searching was done except through the Armed Services Technical Information Agency at Dayton, Ohio, where a few more records were found.

During the search, certain limitations were placed on the kinds of records to be considered. First, they needed to refer to kinetic-energy projectiles, as opposed to HEAT or HEP or other explosive shots designed for the penetration of armor. This retained only the AP, APC, HVAP, and discarding sabot varieties of shot. The caliber of the weapon was required to be between 37 mm and 155 mm. The plate needed to be homogeneous, so face hardened, spaced, and siliceous cored armors were omitted. Finally, no armor was accepted unless at least 1 inch thick.

Selection of Data to be Tabulated

The medium to be used for assembling the data ultimately was to be IBM punched cards which could store 80 numerical or alphabetic characters. It seemed most desirable that each test round should be represented by its individual punched card, and that all working information about the round should be on that card. Since firing records come in a great variety of formats, containing various spectra of information, considerable planning was required to decide what data should be recorded on the cards.

In order to know the origin of each shot card, some notation of reference was needed. Since the basic record is the Firing Record, its number was recorded together with the page and round number of the shot. (The AD or other project reports almost always show the raw data by appending several Firing Records.) In order to show associations of the test, a record was made of the AD report number (if any), or else of the library book number (if any). These reference data made it possible to check or amend the data by returning to the original firing records. They also helped reveal accidental duplication of records. (Many firing records occurred in two or more places in the library.) In addition, a coded notation was added to show the kind of test involved, whether acceptance or experimental, whether testing shot or plate.

The firing records may list many bits of information about the armor plate, such as nominal thickness, actual thickness, type (rolled, cast, wrought), physical properties including surface or cross-sectional hardness, impact tests, chemical composition, heat treatments, manufacturer, heat number, and so forth. Out of all these attributes it was decided that only the plate type, average Brinell hardness of the surface, and nominal thickness were indispensible. The actual thickness was to be recorded and used in the analysis if it were available, but the nominal thickness could be substituted for it. The Charpy or Izod impact test result also was to be recorded as an alternative or supplement to the hardness in case some need or means were found for so using it. Chemical composition and heat treatment were thought to be so complicated of description and so intertwined in their significance that it was unprofitable to include them directly. Along with other data, they could be had by returning to the original records via the reference punches, if this were ever needed.

Description of the shot in most firing records is implied in the model number. Therefore it was decided to describe the shot by assigning each model a three-digit code number. The codes were assigned fairly systematically, so that a person conversant with the system could recognize the shots fairly readily. In records about experimental shots, where many minor variations of shot might be made without changing the model number, double punching with "x" or "y" was added to distinguish between separate varieties. This system allowed these shot varieties to be distinguished or merged, depending on how the computing machines are wired*. In addition, since a fair number of records list hardness measurements of the shot, the Rockwell C hardness at the nose was listed as a bit of stand-by information. No other data about the shot were available broadly throughout the firing records.

Certain test conditions, too, were indispensable for any analysis, namely the obliquity and the striking velocity. Striking velocities almost always are reported to the nearest foot per second, so they were taken in that form for the present analysis. It was intended to adjust those velocities by an appropriate factor (the square root of the ratio of nominal and actual plate thicknesses) in order to compensate for irregularities in the plate thickness. In this way, the tests could be divided efficiently into only a few plate-thickness groups. The obliquities, too, needed to be divided into a few groups, but this was accomplished merely by rounding the obliquity to the nearest multiple of 5 degrees. In most of the firing records, the obliquities were already rounded in this form. It might have been better to record more precise obliquities, when available, on the punched cards, planning to compensate for obliquity roundoff by performing a velocity adjustment, but this was not done, at least partly because of scarcity of precedent. One other test condition which is reported in connection with climatic tests is the temperature. This was eliminated in the present study by omitting the cold weather tests.

Another test specification commonly recorded is the weapon used in firing the shot. Since the rifling of the weapon has been a matter of occasional interest in plate penetration, presumably because of the effect of yaw, it was decided to keep a record of the weapon. To this end, each model of weapon was assigned a two-digit code, but preference was given to the tube model number in case that differed from the weapon model number.

*For example, the AP 90 mm M77 was assigned Code 511. The Code 51$\dot{1}$ meant the same shot without a windshield. The computing machines recognize the latter code as 51J or 511, depending on the wiring.

Editing the Test Results

The result of a given test is, of course, a vital part of the test record. For penetration tests, the result is usually described by saying whether the penetration is partial or complete, but several definitions of completeness have been used. This ambiguity is most unfortunate when a synthesis of data is being attempted, such as in the present project.

In order of severity, the criteria commonly used for completeness of penetration are (a) the Navy criterion which demands that at least half the weight of the projectile shall pass through the plate; (b) the protective criterion which requires that some fragment shall perforate a weak screen placed a short distance behind the target plate (the screen material and thickness seem to vary somewhat); (c) the Army criterion which requires only that light shall show through the hole in the plate when the shot is removed.

The firing records for penetration tests show evaluations of completeness by at least one of these criteria, but no one criterion is common to all the records. Firing records often rate a few rounds for completeness by two or more criteria directly or implicitly, but it is more common to use just one criterion chosen according to the purpose of the test. The firing records also usually describe several results on the plate, such as extent of bulge, cracking, spalling, and hole size, but the emphasis and thoroughness of description varied widely with the observer. From all these bits of information, it was necessary in the present work to construct a uniform penetration rating for each test round.

The Army criterion seemed to be most commonly used in the better firing records assembled for this study. Moreover, it appeared that the Army criterion could be applied most satisfactorily when ratings needed to be inferred from the other descriptive material. Therefore, it was decided to try to rate every round for completeness of penetration by the Army criterion. Ratings by the other criteria were to be recorded when they were shown explicitly or evidently intended to be implied by the author of the firing record.

On the basis of experience in reading the records, some rules were developed for deducing an Army penetration rating. Except when there was clearly some unusual spalling, CP(P)* was taken to imply CP(A). If the only rating shown was PP(N) or PP(P), then the question was referred to the descriptive matter. Any measurable hole on the rear implied CP(A). Also, when there was mention of a large bulge on the plate with punching started or with a substantial crack (longer than the plate thickness), this was taken to imply CP(A), unless it appeared that the author was unduly lavish in his descriptions. On the other hand, the rating was set at PP(A) if a cracked bulge was only medium or small, or if the crack was very short. This method of assigning Army ratings by noting bulges and cracks was checked often when Army ratings were given in the firing records, and the method appeared moderately dependable. Occasionally, when protective ratings were given alone without any other descriptive matter, they were assumed to coincide with Army ratings, but fortunately this expedient was not needed often. Rarely, in view of persistent doubt about it, no rating was assigned.

*That is, a complete penetration CP by the protective criterion (P).

One other relevant test result appeared to be the rupture of the projectile. For example, several test programs have distinguished between ballistic limits for shattered as opposed to unshattered projectiles, and the Project Thor analysis distinguished between broken and intact projectiles. Therefore, in the present project, a brief record of projectile rupture was included for each test. Five classes were recognized: intact, broken but not shattered, nose shattered, other shatter, and no comment. The firing record descriptions varied, so the classification was sometimes difficult, but plausible guesses could be made.

In order to prepare the data for keypunching onto cards, worksheets were prepared on which an editor could assemble whatever information he could gather from any firing record. The worksheets were arranged in the order that was to be used on the punched cards. Vertical columns were allowed for the following kinds of information:

Class of Information	Card Columns
Reference Data	
Library Number	
Book Number or AD Number	1-8
Page Number in Library Book	9-12
Kind of Test (Plate Experiment, etc.)	13
Firing Record	
Record Number	14-23
Page Number	24, 25
Round Number	26, 27
Active Identification	
Shot (code for caliber, type, model)	31-33
Test Obliquity	34, 35
Plate Type	36
Nominal Plate Thickness (to 0.01 in.)	37-40

Class of Information	Card Columns
Active Data	
Actual Plate Thickness (to 0.01 in.)	41-44
Plate Hardness, Brinell	52-54
Striking Velocity	62-65
Penetration Rating (Navy, Protective, or Army)	+ or - in 68, 69, or 70
Occasional Reference Data	
Projectile Rupture Code	71
Weapon Code	72,73
Plate Impact, Charpy or Izod	74,75
Shot Hardness, Rockwell C, on Nose	76-78

The worksheets served not only as a place to store data but also as a reminder of the data that were being sought. This latter function was really important since the information was often scattered throughout a report, and at times had to be searched out of more than one report. Since several people did the work of editing, and they could not afford individual decisions on the problems which kept arising, the problems too were jotted onto the worksheets until they could be settled.

Considerable pains were taken to get all the really necessary information about as many valid test rounds as possible. Information regarded as necessary was that listed under Active Identification and Active Data. If entries under those headings could not be completed, the test was rejected, except for a few that were admitted without the Brinell rating. Another reason often used for rejecting a test was that it was really not a penetration test. This objection applied to most projectile-through-plate tests, and tests involving proof projectiles. Still other tests were rejected because they were isolated tests with poorly rated experimental projectiles.

When the firing records reported ballistic limits computed on the rounds reported therein, those limits too were jotted on the margin of the worksheets.

While the editing was performed by several people, it was checked in the end by one person who attempted to insure uniformity as well as accuracy of the work. Then the worksheets were sent to keypunch operators who punched the data on cards and then verified the punching. In this way, reasonable accuracy seems to have been achieved in the punched data, despite its scattered origins. Some mistakes were found subsequently in the punched data, but they have been relatively few.

The precise number of reports edited does not mean much, because the number of rounds per report varied from 2 for many acceptance tests up to about 640 for one armor report (AD 679). Nevertheless, it may give some idea of the editing task to state that the following approximate number of records were edited:

Kind of Record	Approximate Number
AD Reports	45
Project Reports	10
Firing Records of Substantial Experiments	
With Armor	80
With Projectiles	80
Shot Acceptance Tests	1850
Plate Acceptance Tests	750
Total	~ 2800

Classes of Data Found

The purpose of this project was to combine the data from the many reports that were edited, and to examine them for pattern and consistency. To gage this undertaking, it is helpful to know how many kinds of tests were found reported in the reference records. A résumé of the kinds of tests is given in Table 1. It can be seen there that about 50 principal models of shot were encountered, but that if one counts all the variations of these shot, there were over three times that many kinds of shot. (The precise number of distinct shot varieties is hard to know, because some minor variations were merged in the editing process, and other variations probably were not mentioned explicitly in the firing records.) When one counts how many tests were made with each of these shot varieties, separating the tests into groups according to armor type (rolled or cast), plate thickness (rounded to one of the standard values), and obliquity (rounded to a multiple of 5 degrees), he finds that over 1000 different kinds of tests were reported.*

The great diversity of tests can be reduced by observing that not all varieties of shot need to be analyzed separately. Thus, it appears reasonable to merge results from firings of the same shot with and without windshield, since it has been observed often that the windshield does not much affect the shot's ability for plate penetration at a given striking velocity. Again, shot designers have decided often that there was little

*Unfortunately, a small part of the material gathered for this project remained unedited to the end. The reason for this failure was usually that the tests described scattered tests with unusual kinds of shot. A brief listing of the unedited reports is included in the Appendix, along with the condensed list of material that was edited.

difference between one or more closely related shot varieties, and usually there are too few data altogether to dispute that viewpoint. Since large groups of data are to be preferred for the present analysis, several of these closely related shots were lumped together when they were employed in otherwise equivalent tests. Whenever a serious analysis of any particular test was planned, then considerable care was exercised to keep the lumped shots as compatible as possible. However, in some cases (notably the HVAP, 76 mm "specials") where no close analysis seemed feasible, even dissimilar shots were lumped together in order to provide a brief résumé of the data. These processes of lumping shots account for the fact that the number of analyses shown in Table 1 is substantially less than the number of kinds of tests.

Broadly speaking, each of the various kinds of tests was subjected to one of three kinds of analysis, chosen according to the quantity and quality of the data. Each of these analyses was intended to estimate the striking velocity at which half of the rounds could be expected to penetrate completely. Groups with enough tests (perhaps 25 rounds or more), fairly well distributed with respect to plate hardness, were treated with a probit analysis, specially planned to account for variations with plate hardness. Good smaller groups, especially ones involving small ranges of plate hardness, were treated with an ordinary probit analysis. Groups with only a few tests (less than about 12), or with very irregular patterns, were treated with simple analyses of familiar form, such as taking average velocities of a few partial and complete penetrations. A breakdown of the kinds of analyses applied to the various cases is shown in Table 1. Details regarding method are given in the next section.

Table 1 also shows how many rounds of each main variety of shot were accepted for analysis. Numerous others were not accepted for analysis in the end, usually because they were from shot acceptance tests where the rounds were fired deliberately at velocities considerably above the ballistic limit.

TABLE 1. SUMMARY OF CASES EDITED FOR EACH SHOT

Projectile			Number of Tests				Number of Analyses			
			Shot	Test	Rounds	Rounds	Probits		Simple	
Class	Cal, mm	Model	Kinds	Kinds	Used	Omitted	w/BHN	w/o BHN	Analysis	Total No.
AP	37	M74	1	26	2249	1024	5	8	13	26
		M80	1	1	0	73				0
	57/40	Taper[a]	1	10	67				11	11
	57	M70	2	43	2153	3928	14	14	12	40
	75	M72	2	32	1594	2761	5	3	22	30
		T43	2	4	16				2	2
		T148	9	32	134				12	12
		T149	3	12	92				12	12
	76	M79	1	22	283	937	4	4	14	22
		T128E6 (M339)	1	27	261			4	23	27
		T166	7	22	70				22	22
	90	M77	2	33	676	575	5	6	20	31
		T33	7	32	968	26		12	12	24
		T33E7	14	53	734	77		4	49	53
		T43	1	2	23				2	[illegible]
		T54E1	1	32	617		3	15	14	3[illegible]
	105	T182	4	7	58				2	2
	120	T116	4	46	412			3	43	46
	155	M112	1	14	222	234	1	1	10	12
	6 in.	Mk XXVII	1	3	11	38			2	2
APC	37	M51	1	40	1792	26	18	7	15	40
	57	M86	2	55	1503		16	9	26	51
	75	M61	1	17	72	1489		1	14	15
		T42	1	2	6				2	2
	76	M62	1	43	1012	235	11	10	21	42
	90	M82	6	59	1240		8	7	36	51
		T25	1	1	7				1	1
		T26	1	1	8				1	1
		T27	1	1	8				1	1
		T28	1	1	7				1	1
		T39	13	32	310		1	3	5	9
		T50	2	16	101			1	1	2
		T50E1	2	37	616		2	11	23	36
	105	T13	3	8	20				4	4
		T32E1	1	4	73			2	2	4
	120	T14	8	35	270			4	20	24
HVAP	75	T27	1	4	15				4	4
	76	M93	1	9	119		1	2	4	7
		T4	4	20	200			1	17	18
		Special	15	46	177				6	6
		T29	5	7	36				7	7
		T66E3	1	3	25	176			[illegible]	2
		M331,DS	6	18	152			[illegible]	13	18
	90	M304	2	33	763	392	2	12	21	35
		M332	1	3	51	80			3	3
		T30	3	14	121	110	1	1	12	14
		T44	1	13	145		1	1	11	13
		T53	1	2	9				2	2
		T65,DS	1	1	5				1	1
		T137,DS	14	30	235			1	20	21
	105	T29E4	1	5	25				5	5
	155	T35	[illegible]	7	26				7	7
Totals		52	176	1028	20,069	12,109	98	152	609	894

(a) This projectile is for a weapon with a tapered bore. See O P 5029

EVALUATION OF BALLISTIC LIMITS

Probit Analysis for Substantial Tests

Choice of Formula for Fitting Penetration Data

The ordinary method of evaluating a ballistic limit is to fire enough rounds to get a certain number of partial and complete penetrations within some predetermined velocity interval, and then to average the velocities of those rounds. This method depends on the notion that there is a fairly definite velocity below which the shot will not penetrate the plate completely, and above which it will. However, it is well known that there is really a zone of velocities in which mixed results can be expected. To put it differently, the probability of getting a complete penetration is indeed a function of the striking velocity, but it may be quite different from a step function jumping from 0 to 1.

The great majority of test situations have been the subject of so little firing that the probability of success (i.e., complete penetration) has hardly begun to be measured at any particular level of the striking velocity. However, among the test situations where many rounds have been fired, a common result is that the probability of success, as a function of velocity, rises slowly at first, then rapidly, and then slowly approaches unity, thus approximating a cumulative normal distribution. The slope of the central portion of the curve varies among test situations, and for some cases where shattering of the shot intervenes, the curve may drop again to some low value before it rises finally to unity. This matter of "shatter gaps" is one which will be treated separately later (and then only briefly), since the subject is difficult enough without it. For the present, attention will be restricted only to cases where the probability curve follows a cumulative normal distribution fairly well.

To rationalize this shape for the probability curve, one may assume that whenever a shot is fired there is some critical velocity above which the shot will penetrate completely, below which it will not, and that these critical velocities are normally distributed for repeated rounds under nominally identical firing conditions. This distribution of critical velocities may be attributed to minor, unseen variations in the physical makeup of the shot and the portion of plate which it strikes. Then if $\overline{v}$ and σ are the mean and standard deviation of these critical velocities, the probability of success with a shot at velocity v is:

$$p = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} e^{-\lambda^2/2}\, d\lambda, \text{ where } t = (v - \overline{v})/\sigma .$$

This is the cumulative normal distribution. The quantity $\overline{v}$ is also the velocity at which half of the rounds would achieve complete penetration, and is thus essentially just a refinement of the ordinary concept of the ballistic limit

It has often been observed, too, that the ballistic limit varies with the hardness of the plate, and the NPL formula quoted earlier gives an empirical law for that variation. However, that law was derived for small shot and thin plate, and it can hardly be extrapolated to all cases of interest here since the denominators of two of its terms ($65-\theta$ and B_0-B) can vanish in the present range of interest. Nevertheless, in order to get an idea of the influence of plate hardness on the ballistic limit, that limit was plotted as a function of hardness, using the NPL formula and several combinations of the other parameters. Most of the curves can hardly be distinguished from parabolas opening downward. This suggests that a parabolic relation between $\bar{v}$ and the hardness h is a reasonable form to use in striving for an empirical correlation of the armor penetration data. This type of relation was tested further by comparing it with actual penetration data, and it appeared to serve as well as any other acceptably simple relation. Therefore, it is here assumed further that:

$$\bar{v} = k + ah + bh^2 ,$$

where k, a, and b are constant.

Maximum Likelihood Solution for the Ballistic Limit

Suppose now that a group of tests have been performed at velocities v_i with associated plate hardnesses h_i ($i = 1, 2, \ldots, n$), and that each has been rated as yielding a complete or partial penetration. It is required to estimate the parameters k, a, b, and σ which best account for this set of results. The method which will be applied is a form of probit analysis.* First observe that if our assumptions regarding critical velocities and ballistic limits are valid, then the probability of success with the i^{th} round is $p_i = p(t_i)$, where $t_i = (v_i - k - ah_i - bh_i^2)/\sigma$. The probability of achieving all the observed results is:

$$P = \prod_{i=1}^{n} p_i^{\delta_i} q_i^{1-\delta_i}, \quad q_i = 1 - p_i ,$$

where $\delta_i = 1$ for a success and 0 for a failure. The likelihood function L is defined as the logarithm of P, that is

$$L = \sum_{i=1}^{n} [\delta_i \ln p_i + (1-\delta_i) \ln q_i] .$$

The plan for finding k, a, b, and σ is to choose them so as to maximize L from among all the values it can have when the velocities v_i, hardnesses h_i, and rating numbers δ_i are the ones observed in the actual experiments.

* Cf., Finney, D. J., Probit Analysis, especially Appendix II, Cambridge University Press, London ([illegible]). [illegible] the present one, but without variations of hardness, is given by A. Golub and F. E. Grubbs, [illegible] and Its Precision, Ballistic Research Laboratories Technical Note No. [illegible] (March [illegible]).

The solution $(k^*, a^*, b^*, \sigma^*)$ is wanted which makes

$$\frac{\partial L}{\partial k} = \frac{\partial L}{\partial a} = \frac{\partial L}{\partial b} = \frac{\partial L}{\partial \sigma} = 0 \quad .$$

However, since these equations involve several transcendental functions of the unknowns, it is not possible to solve them directly. Therefore, it is expedient to begin with an estimated solution $(k_1, a_1, b_1, \sigma_1)$ and to seek corrections for it. Expanding the derivatives of L as power series around the estimated solution, there follows:

$$\frac{\partial L}{\partial k} = \left(\frac{\partial L}{\partial k}\right)_1 + (k-k_1)\left(\frac{\partial^2 L}{\partial k^2}\right)_1 + (a-a_1)\left(\frac{\partial^2 L}{\partial k \partial a}\right)_1 + (b-b_1)\left(\frac{\partial^2 L}{\partial k \partial b}\right)_1 + (\sigma-\sigma_1)\left(\frac{\partial^2 L}{\partial k \partial \sigma}\right)_1 ,$$

and similar equations for the other derivatives. If the estimated solution is not too far from the required solution, then the series truncated at this length are valid there, so that:

$$(k^*-k_1)\left(\frac{\partial^2 L}{\partial k^2}\right)_1 + (a^*-a_1)\left(\frac{\partial^2 L}{\partial k \partial a}\right)_1 + (b^*-b_1)\left(\frac{\partial^2 L}{\partial k \partial b}\right)_1 + (\sigma^*-\sigma_1)\left(\frac{\partial^2 L}{\partial k \partial \sigma}\right)_1 = -\left(\frac{\partial L}{\partial k}\right)_1 ,$$

and there are three other similar equations. These equations are linear in the corrections k^*-k_1, a^*-a_1, b^*-b_1, and $\sigma^*-\sigma_1$. Solving for these, and adding them to the first estimates yields improved estimates of the desired solution. The correction process can be repeated until the corrections become negligible, and the last estimates are then the desired solution $(k^*, a^*, b^*, \sigma^*)$.

In order to find the corrections k^*-k_1, and so forth, one needs the second derivatives of L. To get these, note first that if θ_1 and θ_2 are any two of the parameters k, a, b, or σ, then:

$$\frac{\partial^2 L}{\partial \theta_1 \partial \theta_2} = \sum_{i=1}^{n} \left[\frac{\partial^2 p_i}{\partial \theta_1 \partial \theta_2} \cdot \frac{\delta_i - p_i}{p_i(1-p_i)} - \frac{\partial p_i}{\partial \theta_1}\frac{\partial p_i}{\partial \theta_2} \cdot \frac{p_i + \delta_i(1-2p_i)}{p_i^2 (1-p_i)^2} \right] .$$

A convenient notation is:

$$Z_i = \frac{1}{\sqrt{2\pi}} e^{-t_i^2/2} , \quad t_i = (v_i - k - ah_i - bh_i^2)/\sigma \quad .$$

Then,

$$\frac{\partial^2 p_i}{\partial \theta_1 \partial \theta_2} = Z_i \frac{\partial^2 t_i}{\partial \theta_1 \partial \theta_2} - t_i Z_i \frac{\partial t_i}{\partial \theta_1}\frac{\partial t_i}{\partial \theta_2} ,$$

and

$$\frac{\partial L}{\partial \theta_1 \partial \theta_2} = \sum_{i=1}^{n} \left[\frac{\delta_i - p_i}{p_i(1-p_i)} \left(Z_i \frac{\partial^2 t_i}{\partial \theta_1 \partial \theta_2} - t_i Z_i \frac{\partial t_i}{\partial \theta_1}\frac{\partial t_i}{\partial \theta_2} \right) - Z_i^2 \frac{\partial t_i}{\partial \theta_1}\frac{\partial t_i}{\partial \theta_2} \cdot \frac{p_i^2 + \delta_i(1-2p_i)}{p^2 (1-p_i)^2} \right] . \qquad (a)$$

Now let

$$u_i = \begin{cases} -\ Z_i/p_i \text{ for a success} \\ +\ Z_i/q_i \text{ for a failure} \end{cases}, \text{ and}$$

$$w_i = u_i\, t_i - u_i^2 .$$

Then, recalling that $\delta_i = 1$ for success, 0 for failure, it follows:

$$\frac{\partial^2 L}{\partial\theta_1 \partial\theta_2} = \sum_{i=1}^{n} \left[-\ u_i \left(\frac{\partial^2 t_i}{\partial\theta_1 \partial\theta_2} - t_i \frac{\partial t_i}{\partial\theta_1} \frac{\partial t_i}{\partial\theta_2} \right) - u_i^2 \frac{\partial t_i}{\partial\theta_1} \frac{\partial t_i}{\partial\theta_2} \right]$$

$$= \sum_{i=1}^{n} \left[-\ u_i \frac{\partial^2 t_i}{\partial\theta_1 \partial\theta_2} + w_i \frac{\partial t_i}{\partial\theta_1} \frac{\partial t_i}{\partial\theta_2} \right] .$$

Thus the second derivatives of L with respect to the various parameters are:

$$L_{kk} = \sigma^{-2} \sum w_i ,$$

$$L_{ka} = \sigma^{-2} \sum w_i\, h_i ,$$

$$L_{kb} = \sigma^{-2} \sum w_i\, h_i^2 ,$$

$$L_{k\sigma} = \sigma^{-2} \sum (w_i\, t_i - u_i) ,$$

$$L_{aa} = \sigma^{-2} \sum w_i\, h_i^2 ,$$

$$L_{ab} = \sigma^{-2} \sum w_i\, h_i^3 ,$$

$$L_{a\sigma} = \sigma^{-2} \sum (w_i\, t_i - u_i)\, h_i ,$$

$$L_{bb} = \sigma^{-2} \sum w_i\, h_i^4 ,$$

$$L_{b\sigma} = \sigma^{-2} \sum (w_i\, t_i - u_i)\, h_i^2 ,$$

$$L_{\sigma\sigma} = \sigma^{-2} \sum (w_i\, t_i^2 - 2u_i\, t_i) .$$

Letting $\delta k = k^* - k_1$, $\delta a = a^* - a_1$, $\delta b = b^* - b_1$, and $\delta\sigma = \sigma^* - \sigma_1$, the system of equations that must be solved for the corrections is:

$$(L_{kk})_1\, \delta k + (L_{ka})_1\, \delta a + (L_{kb})_1\, \delta b + (L_{k\sigma})_1\, \delta\sigma = -\left(\sigma \sum u_i\right)_1$$

$$(L_{ka})_1\, \delta k + (L_{aa})_1\, \delta a + (L_{ab})_1\, \delta b + (L_{a\sigma})_1\, \delta\sigma = -\left(\sigma \sum u_i\, h_i\right)_1$$

$$(L_{kb})_1\, \delta k + (L_{ab})_1\, \delta a + (L_{bb})_1\, \delta b + (L_{b\sigma})_1\, \delta\sigma = -\left(\sigma \sum u_i\, h_i^2\right)_1$$

$$(L_{k\sigma})_1\, \delta k + (\ [illegible]\ )\, \delta a + (L_{b\sigma})_1\, \delta b + (L_{\sigma\sigma})_1\, \delta\sigma = -\left(\sigma \sum u_i\, t_i\right)_1 .$$

Solving these equations by hand calculations would be possible but laborious, so a program was prepared to do the work with an IBM Type 650 Magnetic Drum Data Processing Machine. The plan of the program required first that an initial estimate should be made for each of the parameters. Then, as the card for each round was fed to the calculator, it would compute the contribution that round made to each of the sums appearing in the coefficients of the system of equations.* The only difficulty in this process was in finding the quantities, Z_i/p_i. For these, a table was stored in the machine which enabled the machine to find Z_i/p_i correctly to one whole number and five decimal places. The whole operation proved to be efficient since the calculations performed for each card took about as long as the minimum time to feed a card to the machine. After the entire group of cards had been used, then an end program proceeded to solve for the corrections δk, etc.

In practice, solving for the parameters k, a, b, σ proved to be a delicate art. Unless the first estimated solution was quite good, the iteration procedure might never converge. Therefore, all the penetration tests analyzed by this technique were first graphed, using an automatic plotter, and initial estimates of the parameters were made from the graphs. Even with this good beginning, some cases failed to converge, presumably because either the normal distribution of critical velocities or the parabolic variation with hardness was not a good assumption. For nonconvergent cases, the only recourse was to divide the data into smaller groups, chosen as logically as possible, and to analyze the subgroups separately. Another rare cause for failure appeared when a parabola could be fitted to the data so as to separate entirely the complete and partial penetrations. This, of course, makes σ indeterminate; so for these cases a parabola was fitted using the fairly arbitrary value of 10 ft/sec for σ.

One further refinement that was added stems from the fact that the parameters k and a are relatively meaningless. For the sake of clarity of meaning in the parameters, it is more desirable to express $\bar{v}$ as:

$$\bar{v} = v_0 + b(h - h_0)^2 .$$

This is the same as the former expression provided:

$$h_0 = -\frac{a}{2b}, \quad v_0 = k - \frac{a^2}{4b} .$$

Since the values of k, a, b, and σ which maximize L correspond by these relations to the values of v_0, h_0, b, and σ which maximize L, the latter values are easily found from the former. The reason for using the parameters k, a, b, σ was merely that they yielded simpler expressions for the second derivatives of L. However, when the parameters are expressed as v_0, h_0, b, and σ, they become respectively the maximum (or minimum) ballistic limit, the optimum (or pessimum) hardness, a measure of sensitivity to changes in plate hardness, and the standard deviation of critical velocities.

* Because of an algebraic error [illegible] explicit [illegible] in the above expressions for L_{bb}, L_{ab}, and $L_{a\sigma}$ were [illegible] from some early calculations, and [illegible] was [illegible] the coefficients. However, when these terms were included correctly in the later trial calculations, they did not seem to affect the [illegible] speed [illegible] convergence [illegible] is not unreasonable, since the sums of these terms are proportional to the first derivatives of L, and should [illegible] take the maximum likelihood values. In the end, these terms were omitted from the calculations. A similar [illegible] terms occurs in the formulas of Golub and Grubbs.

Precision of the Ballistic Limit

One of the great difficulties besetting the evaluation of ballistic limits has been uncertainty regarding the dependability of the limits as they have been computed in the past. Therefore, when probabilistic evaluations of the limits are being made, as they are here, some estimate of their precision is highly desirable. To get this estimate of precision, we can use a proposition from mathematical statistics, which states that the variances and covariances of the maximum likelihood estimators for the parameters of a population are the elements of the inverse to the Hessian matrix:

$$\left\| -E\left(\frac{\partial^2 L}{\partial\theta_i \partial\theta_j}\right) \right\|,$$

where E( ) denotes an expected value, and θ_i and θ_j represent any two of the parameters being estimated. Restrictions on this proposition are that the number of tests n is sufficiently large, and that to a good approximation*:

$$-E\left(\frac{\partial^2 L}{\partial\theta_i \partial\theta_j}\right) = E\left[\left(\frac{\partial L}{\partial\theta_i}\right)\left(\frac{\partial L}{\partial\theta_j}\right)\right].$$

Regarding sample size, Golub and Grubbs gave an illustration with n = 5, so the present aim to keep n more than or almost 25 is probably fairly conservative. The approximate equality between expected values was deemed plausible by Golub and Grubbs, and seems to be so here too.

Regardless of which set of parameters is used, the equation (a) for $\frac{\partial L}{\partial\theta_1\partial\theta_2}$ is still valid. In particular, we now regard it as applying to the case where θ_1 and θ_2 are any of the parameters v_o, h_o, b, or σ. Since only expected values of the second derivatives are required now, and since $E(\delta_i) = p_i$, it follows from equation (a) that

$$-E\left(\frac{\partial^2 L}{\partial\theta_1 \partial\theta_2}\right) = \sum_{i=1}^{n} \frac{Z_i^2}{p_i q_i} \frac{\partial t_i}{\partial\theta_1} \frac{\partial t_i}{\partial\theta_2}.$$

The required first derivatives are:

$$\frac{\partial t_i}{\partial v_o} = -\frac{1}{\sigma}, \quad \frac{\partial t_i}{\partial h_o} = \frac{2b(h_i - h_o)}{\sigma}, \quad \frac{\partial t_i}{\partial b} = \frac{-(h_i - h_o)^2}{\sigma}, \quad \frac{\partial t_i}{\partial\sigma} = -\frac{t_i}{\sigma}.$$

Using these expressions for the derivatives, and the notation:

$$U_i = \frac{Z_i^2}{p_i q_i},$$

* This statement of this proposition parallels that of Golub and Grubbs, op. cit., p. 9. For a more expanded, but less direct statement, see Kendall, M. G., The Advanced Theory of Statistics, Volume II, Sections 17.46 and 17.26, Griffin and Co., Ltd., London (1946).

it follows that the required Hessian matrix is:

$$\left\| \begin{matrix} \frac{1}{\sigma^2}\sum U_i & -\frac{2b}{\sigma^2}\sum U_i(h_i-h_o) & \frac{1}{\sigma^2}\sum U_i(h_i-h_o)^2 & \frac{1}{\sigma^2}\sum U_i t_i \\ -\frac{2b}{\sigma^2}\sum U_i(h_i-h_o) & \frac{4b^2}{\sigma^2}\sum U_i(h_i-h_o)^2 & -\frac{2b}{\sigma^2}\sum U_i(h_i-h_o)^3 & -\frac{2b}{\sigma^2}\sum U_i(h_i-h_o)t_i \\ \frac{1}{\sigma^2}\sum U_i(h_i-h_o)^2 & -\frac{2b}{\sigma^2}\sum U_i(h_i-h_o)^3 & \frac{1}{\sigma^2}\sum U_i(h_i-h_o)^4 & \frac{1}{\sigma^2}\sum U_i(h_i-h_o)^2 t_i \\ \frac{1}{\sigma^2}\sum U_i t_i & -\frac{2b}{\sigma^2}\sum U_i(h_i-h_o)t_i & \frac{1}{\sigma^2}\sum U_i(h_i-h_o)^2 t_i & \frac{1}{\sigma^2}\sum U_i t_i^2 \end{matrix} \right\|$$

The elements of the inverse to this matrix are the variances and covariances of the maximum likelihood estimators of the parameters v_o, h_o, b, and σ in that order.

The estimate of the ballistic limit $\bar{v}$ is, of course,

$$\bar{v} = v_o + b(h-h_o)^2 .$$

Since $\bar{v}$ is a function of parameters that have been estimated to within known variances and covariances, it follows* that the variance of this estimator for $\bar{v}$ can be found from:

$$\sigma^2_{\bar{v}} = \left(\frac{\partial \bar{v}}{\partial v_o}\right)^2 \sigma^2_{v_o} + \left(\frac{\partial \bar{v}}{\partial h_o}\right)^2 \sigma^2_{h_o} + \left(\frac{\partial \bar{v}}{\partial b}\right)^2 \sigma^2_b$$

$$+ 2\frac{\partial \bar{v}}{\partial v_o}\frac{\partial \bar{v}}{\partial h_o}\sigma^2_{v_o,h_o} + 2\frac{\partial \bar{v}}{\partial h_o}\frac{\partial \bar{v}}{\partial b}\sigma^2_{h_o,b} + 2\frac{\partial \bar{v}}{\partial b}\frac{\partial \bar{v}}{\partial v_o}\sigma^2_{b,v_o}$$

$$= \sigma^2_{v_o} + 4b^2(h-h_o)^2\sigma^2_{h_o} + (h-h_o)^4\sigma^2_b$$

$$- 4b(h-h_o)\sigma^2_{v_o,h_o} - 4b(h-h_o)^3\sigma^2_{h_o,b} + 2(h-h_o)^2\sigma^2_{b,v_o} .$$

This expression makes it possible to state a variance for the estimate of the ballistic limit $\bar{v}$ as a function of hardness, at least over the range of plate hardnesses that appear in the case being analyzed.

As a conclusion to the computing for tests having variable plate hardness, a supplementary program was prepared to find the parameters v_o, h_o, b, σ and their variances and covariances. The results for all the cases analyzed in this way are shown in Table 2. Values of $\sigma_{\bar{v}}$ for three levels of hardness covering the range of the test data are incorporated later in Table 3. If values of $\sigma_{\bar{v}}$ are desired at other hardness levels,

* Cf., Hald, A., Statistical Theory With Engineering Applications, p. 11*, John Wiley and Sons, New York (1952).

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TABLE 2. BALLISTIC LIMITS OBTAINED BY PROBIT ANALYSES INCLUDING VARIATION OF PLATE HARDNESS

Shot Cal, mm	Shot Model	Nom. Obl., deg	Plate Thickness, in.	Ballistic Limit Parameters V_b, ft/sec	h_b, BHN	$b \times 10^5$, ft/sec/(BHN)^2	σ, ft/sec	Variances of Estimates of Ballistic Limit Parameters $\sigma^2_{V_b}$	$\sigma^2_{h_b}$	$\sigma^2_b \times 10^8$	$\sigma_{V_b h_b}$	$\sigma_{V_b b} \times 10^4$	$\sigma_{h_b b} \times 10^4$	σ^2_σ	Number of Rounds
AP Shot Versus Rolled Homogeneous Armor															
37	[illegible]	[illegible]	1.50	1304	300	-1972	53	41	5	661	3	-130	[illegible]	27	546
			2.50	2046	244	7012	[illegible]	9670	1500	[illegible]	1904	14194	27100	30012	27
57	[illegible]	[illegible]	2.50	1540	[illegible]	-3415	[illegible]	106	53	7007	40	-720	-130	161	[illegible]
			3.00	1023	296	-2796	79	112	10	[illegible]	16	-106	-70	91	210
			4.00	2205	286	[illegible]	[illegible]	202	6	3795	10	-707	-44	202	42
		30	3.00	[illegible]	402	1124	56	17470	7707	4012	-1401	[illegible]	-615	319	100
		35	3.00	2405	440	[illegible]	147	11700	[illegible]	[illegible]	-6794	13477	[illegible]	2044	90
		40	2.50	2040	304	-7300	374	17156	76	132644	-119	-40411	[illegible]	15006	87
			3.00	2610	300	7726	61	291	46	30133	-26	103	-1194	374	78
		50	2.00												
			2.50	2701	285	-1900	97	1001	220	[illegible]	-100	-3002	-670	922	63
75	[illegible]	[illegible]	2.50	1104	288	-3017	41	98	63	[illegible]	71	-300	-446	125	55
			3.00	1300	297	[illegible]	35	155	79	773	61	-207	-46	63	79
			4.00	1715	273	-2730	35	136	30	4171	26	-364	[illegible]	118	41
76	[illegible]	[illegible]	4.00	[illegible]	180	[illegible]	79	23700	[illegible]	[illegible]	35219	29400	52446	4729	18
		30	2.50	1707	304	-2530	96	1906	[illegible]	[illegible]	304	196	2326	1290	32
		45	2.50	[illegible]	[illegible]	-1107	–	(Parabola fitted without overlap by PP's or CP's)							21
		60	2.50	2147	745	101	16	1791304	[illegible]	[illegible]	-2130054	[illegible]	[illegible]	90	26
90	[illegible]	[illegible]	4.00	[illegible]	261	[illegible]	73	570	81	12204	[illegible]	-1004	-30	535	37
		45	2.50	[illegible]	282	-1407	35	377	115	0217	[illegible]	-1414	-443	118	38
		65	2.50	[illegible]	[illegible]	[illegible]	–	(Parabola fitted with little overlap by PP's or CP's)							23
90	T96E1	[illegible]	3.00	2700	287	[illegible]	41	277	55	4077	5	-430	-464	223	41
		[illegible]	4.00	2735	700	252	94	[illegible]	[illegible]	[illegible]	-7954702	551[illegible]	-613054	1937	41
105	[illegible]	30	4.00	1675	402	-670	124	[illegible]	[illegible]	[illegible]	[illegible]	133708	09141	1903	45
APC Shot Versus Rolled Homogeneous Armor															
37	[illegible]	[illegible]	1.00	1207	[illegible]	-2307	15	72	19	[illegible]	3	[illegible]	-95	[illegible]	[illegible]
			1.12	[illegible]	[illegible]	-1077	[illegible]	[illegible]	42	[illegible]	10	[illegible]	[illegible]	144	[illegible]
			1.30	[illegible]	[illegible]	[illegible]	[illegible]	74	576	717	92	17	540	32	67
			2.50	2122	94	[illegible]	13	21077	[illegible]	1679	[illegible]	[illegible]	[illegible]	26	23
		20	1.00	[illegible]	[illegible]	-1500	[illegible]	120	30	[illegible]	18	-221	-156	92	35
			1.50	1777	[illegible]	-427	[illegible]	[illegible]	[illegible]	1535	1771	091	2057	[illegible]	45
		30	1.00	[illegible]	[illegible]	92	23	90	[illegible]	[illegible]	[illegible]	[illegible]	-3726	90	34
			1.50	[illegible]	245	[illegible]	[illegible]	192	201	2711	[illegible]	194	032	128	[illegible]
		40	1.00	[illegible]	201	[illegible]	92	[illegible]	1476	[illegible]	242	97	1461	136	53
			1.12	[illegible]	304	[illegible]	123	[illegible]	7700	[illegible]	4140	5207	11516	1628	[illegible]
			1.50	[illegible]	225	2217	[illegible]	[illegible]	494	[illegible]	451	1127	1100	156	58
		45	1.50	[illegible]	-22	670	65	[illegible]	[illegible]	[illegible]	[illegible]	511731	240256	475	[illegible]
		50	1.00	[illegible]	[illegible]	[illegible]	121	940	215	[illegible]	-26	-1073	[illegible]	072	[illegible]
			1.12	[illegible]	307	-2240	150	[illegible]	1505	27006	079	1702	6107	2261	[illegible]

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TABLE 2. (Continued)

Cal., mm	Shot Model	Nom. Obl., deg	Plate Thickness, in.	V_{bp}, ft/sec	h_{bp}, BHN	$b \times 10^{?}$, ft/sec(BHN)^2	σ, ft/sec	$\sigma^2_{V_b}$	$\sigma^2_{h_b}$	$\sigma^2_b \times 10^8$	$\sigma^2_{V_b h_b}$	$\sigma^2_{V_b b} \times 10^4$	$\sigma^2_{h_b b} \times 10^4$	σ^2_σ	Number of Rounds
						APC Shot Versus Rolled Homogeneous Armor (Continued)									
57	[illegible]	[illegible]	1.50	1311	[illegible]	-[illegible]	[illegible]	[illegible]	53	[illegible]	6	-357	-545	176	[illegible]
			2.50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3743	-[illegible]	[illegible]	-[illegible]	[illegible]	21
			3.00	[illegible]	647	[illegible]	21	[illegible]	213[illegible]	1511	-[illegible]	14123	-[illegible]	82	[illegible]
			4.00	[illegible]	[illegible]	-1672	[illegible]	9275	[illegible]	[illegible]	[illegible]	-14128	-2101	16379	[illegible]
		[illegible]	1.50	[illegible]	201	-[illegible]	[illegible]	171	[illegible]	[illegible]	22	-554	-[illegible]	[illegible]	[illegible]
			3.00	2116	[illegible]	[illegible]	-	(Parabola fitted without overlap by PP's or CP's)							[illegible]
		[illegible]	1.50	[illegible]	[illegible]	-[illegible]	27	[illegible]	54	[illegible]	51	-678	-[illegible]	[illegible]	31
			2.50	[illegible]	[illegible]	-[illegible]	[illegible]	[illegible]	321	13[illegible]	-42	-1[illegible]	[illegible]	552	[illegible]
			3.00	[illegible]	[illegible]	-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-3	-1277	[illegible]	1274	[illegible]
		[illegible]	1.50	[illegible]	[illegible]	[illegible]	16	[illegible]	[illegible]	[illegible]	-[illegible]	-255	[illegible]	49	25
			2.50	[illegible]	[illegible]	-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1[illegible]1	2730	[illegible]	[illegible]
		[illegible]	1.50	[illegible]	327	-[illegible]	[illegible]	140	[illegible]	[illegible]	-[illegible]	-347	245	129	[illegible]
			2.00	2770	[illegible]	-[illegible]	[illegible]	7517	[illegible]	[illegible]	-[illegible]	-12[illegible]	-[illegible]	[illegible]	[illegible]
		[illegible]	1.50	[illegible]	315	-[illegible]	101	[illegible]	[illegible]	[illegible]	-1[illegible]	-2744	1729	823	53
[illegible]	[illegible]	[illegible]	2.50	[illegible]	[illegible]	-[illegible]	[illegible]	[illegible]	24	[illegible]31	3	-794	-[illegible]	219	26
			3.00	[illegible]	[illegible]	[illegible]	72	[illegible]	[illegible]	313[illegible]	-[illegible]	51273	-43[illegible]57	12[illegible]	23
		[illegible]	4.00	[illegible]	419	-[illegible]	[illegible]	[illegible]	119153	132[illegible]	[illegible]	[illegible]	125[illegible]	1123	23
		[illegible]	2.50	[illegible]	274	-[illegible]	61	[illegible]	1[illegible]	[illegible]	34	-19[illegible]	-[illegible]	682	23
			3.00	[illegible]	[illegible]	-[illegible]	[illegible]	1211[illegible]	341171	41072	[illegible]	[illegible]	117[illegible]	[illegible]	94
		[illegible]	3.00	[illegible]	[illegible]	-[illegible]	125	[illegible]	61	[illegible]	[illegible]	-2237	-1[illegible]	1911	[illegible]
		[illegible]	1.50	[illegible]	[illegible]	-751	[illegible]	[illegible]	1015	[illegible]17	215	-1511	-[illegible]	771	52
			2.50	[illegible]	[illegible]	-[illegible]	[illegible]	[illegible]	2332	46115	[illegible]	-[illegible]	[illegible]	17336	47
		[illegible]	1.50	[illegible]	[illegible]	-[illegible]	81	[illegible]	137	[illegible]	90	-2[illegible]	-791	771	[illegible]
[illegible]	[illegible]	[illegible]	4.00	[illegible]	[illegible]	-[illegible]	120	4192	[illegible]	[illegible]	144	-15153	-[illegible]	[illegible]	19
		[illegible]	2.50	[illegible]	[illegible]	[illegible]	-	(Parabola fitted with little overlap by PP's or CP's)							17
			3.00	1671	[illegible]	[illegible]	23	[illegible]	[illegible]	21[illegible]	-[illegible]	26226	-[illegible]	43	[illegible]
			4.00	27[illegible]	[illegible]	-[illegible]	274	22[illegible]	370[illegible]	[illegible]212	9114[illegible]	573[illegible]	24[illegible]	11298	52
		[illegible]	2.50	[illegible]	[illegible]	-[illegible]	[illegible]	1119	[illegible]	171[illegible]	[illegible]	-3478	-915	[illegible]	41
			3.00	[illegible]	[illegible]	-[illegible]	17.2	[illegible]	[illegible]	[illegible]	[illegible]	-[illegible]	1124	[illegible]	201
[illegible]	Y[illegible]1	[illegible]	5.00	[illegible]	[illegible]	-77[illegible]	[illegible]	[illegible]	5	[illegible]	-[illegible]	-5[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	3.00												
						HVAP Shot Versus Rolled Homogeneous Armor									
[illegible]	[illegible]	[illegible]	4.00	[illegible]	221	[illegible]	[illegible]	[illegible]	211	[illegible]	[illegible]	-3347	9547	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	6.00	[illegible]	[illegible]	7274	[illegible]	[illegible]	[illegible]	[illegible]	610	[illegible]	[illegible]	1921	165
		[illegible]	4.00	[illegible]	[illegible]	-[illegible]	[illegible]	273	[illegible]	[illegible]	-6	-[illegible]	-[illegible]	171	61
[illegible]	[illegible]	[illegible]	5.00	[illegible]	[illegible]	-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	107	[illegible]	[illegible]	526	21
[illegible]	[illegible]	[illegible]	[illegible]	2775	[illegible]	-[illegible]	-	(Parabola fitted with little overlap by PP's or CP's)							23

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TABLE 2. (Continued)

Shot Cal, mm	Shot Model	Obliquity, deg	Plate Thickness, in.	Ballistic Limit Parameters: [illegible], ft/sec	[illegible]	b x 10[illegible], ft/sec/(deg)²	σ, ft/sec	Variances of Estimates of Ballistic Limit Parameters: [illegible]	[illegible]	[illegible] x 10[illegible]	[illegible]	[illegible] x 10⁴	[illegible] x 10⁴	[illegible]	Number of Rounds
AP Shot Versus Cast Homogeneous Armor															
[illegible]	[illegible]	[illegible]	1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	27	16	[illegible]	7	-177	-174	41	376
			2.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1025	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1012	[illegible]	[illegible]	311	[illegible]
[illegible]	[illegible]	[illegible]	2.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16	9172	11	[illegible]	-137	[illegible]	[illegible]
			3.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11173	2	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	3.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-13	-1722	118	[illegible]	[illegible]
		[illegible]	3.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	2.[illegible]	[illegible]	[illegible]	[illegible]	147	[illegible]	[illegible]	[illegible]	-621	[illegible]	-912	[illegible]	147
[illegible]	[illegible]	[illegible]	3.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	36	[illegible]	[illegible]	[illegible]	[illegible]
			4.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	3.[illegible]	[illegible]	177	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	30117	[illegible]	[illegible]	[illegible]	61
			4.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-137	197	[illegible]	[illegible]	177
[illegible]	[illegible]	[illegible]	4.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7	[illegible]	[illegible]	[illegible]	43
APC Shot Versus Cast Homogeneous Armor															
[illegible]	[illegible]	[illegible]	1.[illegible]	[illegible]	[illegible]	70	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21	53
		[illegible]	1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-146	[illegible]	[illegible]	1473	29
		[illegible]	2.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	297
		[illegible]	1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	57	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	3.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17	[illegible]	31	[illegible]	251	[illegible]	47
[illegible]	[illegible]	[illegible]	4.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1116	5	[illegible]	-42	-14113	[illegible]	[illegible]	46
		[illegible]	2.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	4.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	3.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	67	[illegible]	-241	2223	212
[illegible]	[illegible]	[illegible]	5.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	179	2	[illegible]	-4	[illegible]	[illegible]	[illegible]	[illegible]

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they can be derived from the variances and covariances shown in Table 2. Three other covariances ($\sigma^2_{v_0,\sigma}$, $\sigma^2_{h_0,\sigma}$, $\sigma^2_{b,\sigma}$) were computed, of course, but did not seem necessary for inclusion in the table, since they would be used only for predicting standard errors of ballistic limits at levels other than 50 per cent probability.

In most cases, the values of h_0 shown in Table 2 confirm the idea that the optimum hardness of armor plate is in the vicinity of BHN 300, but there are many exceptions. A common reason for these exceptions is that as the plate hardness increases the projectile tends to shatter more readily, and this raises the ballistic limit. This increase of ballistic limits at the high hardness end of the data is not simply statistical chance, for the values of σ^2_b show that b is generally significantly different from zero, whether b is negative or positive.

The values σ show that the scattering of critical velocities in most of the test situations was substantial. Better than half of them were above 60 ft/sec. Thus the chances for a seemingly erratic result with any small number of tests is reasonably great.

It may be observed too that there were five instances in which the parabola fitted the data with so little overlapping that the probit analysis did not lead to an evaluation of σ or of the variances of the estimates of the parameters. One of the cases (with the HVAP 90 mm T44) was somewhat degenerate in that the data had only three hardnesses, but the other cases involved four to six hardnesses. For the latter cases, the parabola offered a surprisingly convenient fit.

Probit Analysis Without Variation of Hardness

There are many penetration tests that have been performed having so little variation of plate hardness that the preceding analysis is not justified. In this case, a probit analysis without variation of the hardness may still be applied, provided a reasonable number of tests were performed and the results include overlapping velocities of partial and complete penetrations.

An analysis for this case can be had from the broader analysis described earlier, provided it is assumed that a = b = 0, so that $\bar{v} = k$. This means that the maximum likelihood solution now requires finding only two parameters, $\bar{v}$ and σ. If initial estimates $\bar{v}_1$ and σ_1 are available, then the equations for the corrections $\delta\bar{v}$ and $\delta\sigma$ are:

$$\left(L_{\bar{v}\bar{v}}\right)_1 \delta\bar{v} + \left(L_{\bar{v}\sigma}\right)_1 \delta\sigma = -\left(\sigma \sum u_i\right)_1$$

$$\left(L_{\bar{v}\sigma}\right)_1 \delta\bar{v} + \left(L_{\sigma\sigma}\right)_1 \delta\sigma = -\left(\sigma \sum v_i t_i\right)_1$$

where

$$L_{\overline{v}\,\overline{v}} = \frac{1}{\sigma^2}\sum w_i \quad ,$$

$$L_{\overline{v}\,\sigma} = \frac{1}{\sigma^2}\sum (w_i t_i - u_i) \quad ,$$

$$L_{\sigma\sigma} = \frac{1}{\sigma^2}\sum (w_i t_i^{\,2} - 2u_i\, t_i) \quad ,$$

while w_i and u_i are the same funtions of t_i as before, but with $t_i = (v_i - \overline{v})/\sigma$. The variances and covariances in the solutions for $\overline{v}$ and σ after the iteration process is completed are the elements of the inverse of the matrix

$$\left\| \begin{matrix} \frac{1}{\sigma^2}\sum U_i & \frac{1}{\sigma^2}\sum U_i t_i \\ \frac{1}{\sigma^2}\sum U_i t_i & \frac{1}{\sigma^2}\sum U_i t_i^{\,2} \end{matrix} \right\| \quad ,$$

where U_i is as before except for the change in t_i. All these results are equivalent to formulas given by Golub and Grubbs, except for the small differences already noted in $L_{v\sigma}$ and $L_{\sigma\sigma}$.

Very little additional programming was needed to adapt these formulas to machine calculation, because the only requirement was to drop some of the terms that appeared formerly.

This method of analysis was applied to many cases where the accumulated data included as many as 12 rounds, but with little variation in the Brinell hardness number, that is, less than about 50. However, in order to avoid getting unreasonable variances, it was necessary to exclude several cases that were complicated by shatter gaps, or systematic discrepancies from other sources, some unknown.

Results of the calculations ignoring variation of hardness are not tabulated here as a group, because the most significant results, $\overline{v}$ and $\sigma_{\overline{v}}$, are included later in the comprehensive Table 3.

Brief Analysis Used for Cases With Few Data

The methods of probit analysis require a sample reasonably good in both size and [illegible]ion in order to produce useful results. If the sample is too small the logic be-h[illegible] the probit analysis is weak. If there is no overlapping of partial and complete penetrations, then the solution becomes indeterminate. There were many cases of these [illegible] in the data assembled for this project, plus other cases having very irregular data patterns. For these cases some analysis, or at least some method of description, was needed. In order not to overtax the data, simple instead of sophisticated analyses [illegible] desirable.

For cases where there were less than about 12 rounds, or where there was no overlap, it was decided to use the old averaging technique to define a "ballistic limit". This was based, preferably, on six rounds: the three lowest CP's and the three highest PP's. If these lay within an interval of 150 ft/sec, and were the only test velocities in that interval, then their average velocity constituted a good ballistic limit by the ordinary standards, and it was accepted as the ballistic limit for the present study. If this six-round average could not be had, then an average of four rounds within an interval of 100 ft/sec was accepted, or even two rounds within an interval of 50 ft/sec. Accepting these as ballistic limits in the present study does not mean that they have any good or even known degree of accuracy. It means only that these were about as good limits as could be obtained, considering the state of the data. So long as the origin of each limit is stated, the varying definitions of the limits should not cause trouble. Of course, an extra bit of useful information about these simple ballistic limits is the spread of test velocities included, so it was decided that that too should be mentioned for each case.

A moderate number of test conditions have yielded test results that do not follow the ideal scattering of partial and complete penetrations. Sometimes there is an identifiable cause for this, such as shattering. In such a case, a split analysis is sometimes useful, say one for intact or broken shot, and another for shattered shot. It was decided to use a split analysis if that enabled one to give an instructive description of the test results.

In some cases, the partial and complete penetrations were mixed over a wide range of velocities, sometimes over practically the whole of a wide range that was tested. In order to describe this situation, it was decided that a simple statement would be made describing the mixed zone. Such a statement does not pretend to define a ballistic limit, but it does picture the state of the test results.

For cases where the highest PP was considerably below the lowest CP, it was decided merely to state those two velocities. Finally, if there were no CP's, then a highest partial penetration (HPP) could be listed; or if there were no PP's, then the lowest complete penetration (LCP) could be used.

It may be repeated that simple analyses of these sorts do not always give good evaluations of ballistic limits. Oftentimes they may be poor indeed. Good examples of this can be found in long sequences of PP's at successively higher velocities, followed at last by a lone CP. Such a sequence of tests may allow the computation of a simple two-round ballistic limit, but it has little meaning beyond that of identifying a velocity which lies in or near the mixed zone.

Compilation of Ballistic Limits

A comprehensive collection of the results of the analyses performed for the present project is given in Table 3, at the end of the text of this report. Since the table presents a wide variety of results, the user should try to keep in mind what the foundations of the table are.

First it may be said that the objective that was followed in preparing this table was to describe the results of the penetration tests as instructively and concisely as possible. The results were to be in the form of ballistic limits, but even the definition of ballistic limit needed to vary from case to case, depending on the quantity and quality of the data. Methods were needed both for selecting the type of limit and for describing the results of the analysis.

The approximate order of preference for the methods of finding the ballistic limit was:

(1) Probit analysis with variation of hardness

(2) Probit analysis without variation of hardness

(3) Averaging if 6, 4, or 2 rounds, half being CP and half PP within a suitably small interval

(4) Locating the zone of mixed CP's and PP's in the data

(5) Locating the highest partial penetration (HPP) or lowest complete penetration (LCP) if the results were all of one kind.

For each test condition, the analysis was begun by trying the highest seemingly feasible method on this list. If that method failed (say, by lack of convergence of the probit calculation, or by unacceptable scattering of PP's and CP's for simple averaging), then a lower method was applied. At times it was expedient to split a large group of data into smaller subgroups in order to make them manageable. The splitting was done as plausibly as possible, on the basis of shattering, plate hardness, shot hardness, or even distinction between references. Separation according to references (applied twice, both times to data for the APC 37 mm M51) implies that there were real, but unidentified systematic differences between separate series of tests.

Except when parabolas were fitted with negligible overlapping of partial and complete penetrations, all the probit analyses were completed to the point of finding the standard error in the estimate of the ballistic limit. The probit analyses may be identified in Table 4 by the fact that the standard error (SE) is stated. If three ballistic limits, together with their standard errors, are shown by braces as having been derived from the same set of rounds (that is, only one entry for the "number of rounds"), then the analysis was one allowing for parabolic variation of hardness. The levels of plate hardness cited for these parabolic cases are roughly the extreme and middle hardnesses appearing in the reference data.

Limits obtained by averaging are identified by statements such as 6R(124), which would imply that the average was based on six rounds spread over a velocity interval of 124 ft/sec. The remaining types of analyses are identified by self-explanatory statements such as "Mix 3041 to 3463", or "2669 HPP".

The probit analyses were performed by the electronic calculator which, among other things, adjusted the velocity of each round to an equivalent velocity against a plate of standard or "nominal" thickness according to the formula:

$$\text{adjusted velocity} = \text{observed velocity}\left(\frac{\text{nominal thickness}}{\text{actual thickness}}\right)^{1/2} .$$

This formula is probably fairly accurate for the small corrections that were needed. Since these corrections were performed round by round, no further corrections for irregularities of plate thickness are needed in the results of the probit analyses. However, the simpler limits obtained by averaging or location of extreme velocities were evaluated by hand, and the round-by-round thickness correction for them became too burdensome. Therefore, for these simpler analyses, a note is added showing the average plate thickness of the rounds involved in the calculation, if that average was known to differ from the nominal plate thickness. These notes are written briefly in the form like "t 3.03", which would imply that the average plate thickness was 3.03 in.

Since projectile breakup often influences the probability of complete penetration, an effort was made to describe briefly the typical breakup in each case. This is contained in the notes by statements such as:

SI ~ shot generally intact,

SB ~ shot rally broken but not shattered,

SS ~ shot generally shattered,

or by combinations such as:

SI&B ~ some shot intact, some broken

SI&S ~ breakage ranging from intact to shattered.

Many of the rounds edited and keypunched were omitted finally from the analysis, almost always because they were fired in acceptance tests at velocities intended to be significantly above the ballistic limit. However, the existence of the rounds is noted in Table 3 by entries under the cases where they would have appeared had they been used Thus, for the AP 37mm M74 against rolled armor, there appear two entries, "84ARO" and "842ARO", which mean 84 and 842 acceptance rounds omitted. Such entries are sprinkled throughout the table.

When special modifications or lots of shot were used, notes are added in Table 3 identifying these shots, provided such identification was thought to be useful. A special abbreviation was used when the shot hardness was variable. An example of this is "RC61", which means that the hardness was 61 on the Rockwell C scale The hardness listed is that of the nose, or of the bourrelet if the shot were truncated

References to the firing records in each test situation were not included in Table 3, since such an inclusion threatened to obscure the results However, a list of reference reports used for this collection of penetration tests is included in the Appendix

OBSERVATIONS CONCERNING THIS STUDY

Success of the Methods of Analysis

When this pro ct was begun, it could not be anticipated what all might result from putting data from so many sources into one great lump. In order to forestall trouble, as much information as possible was carried regarding each individual test. In consequence, the results are at least moderately consistent and precise. Because these results come from so many test programs, they are also as unbiased as seems possible at present.

In the process of performing the analyses, very many sets of data were studied by persons who wanted to understand those data as much as possible. When the scattering of the data was bad, reasons for this were sought. Only rarely were there cases where different firing records gave noticeably different results without a plausible reason. In only two cases was it thought profitable to split the data according only to the reference, both times involving AD 1084, which seemed to refer to either some very good plate or some very poor shot. The fact that separation according to reference was invoked so seldom seems to imply, on the whole, that combining raw data from many sources was a reasonably successful venture.

Use of the parabolic form for the influence of plate hardness was also reasonably successful. There were relatively few cases where the assumption of this form seemed to deny convergence to the process of probit analysis. When the parabolic form proved too inflexible, it was most often because a sharp increase in projectile shattering occurred as the plate hardness increased. Another occasional difficulty arose when the plate hardnesses went above BHN 350, for then the ballistic limit curve sometimes seemed to descend more rapidly than the parabola.

The assumption of the cumulative normal distribution for probability of complete penetration as a function of striking velocity was moderately successful, but it was often troubled by the occurrence of projectile shattering. A bad example occurred in the data for the APC 57 mm M86 fired against 3-inch R H. plate at obliquity of 35 degrees. In this case 105 rounds were recorded for Brinell hardnesses 295 to 335, having velocities between 2450 and 2800 ft/sec. At no velocity did the probability of a CP seem to rise above 40 per cent, and it seemed to fall to zero at both ends. The shot breakage in this case ranged from intact to shattered, but no record of the breakage was available for many of the rounds that were fired.

As a foundation for statistical analysis of the penetration tests, the assumption of the cumulative normal distribution seems as good as any reasonably simple assumption that can be made, but a highly detailed analysis of multitudinous data (more than exist now) would probably use a more flexible form for this probability function

The standard errors in the ballistic limits vary widely, but are typically from 15 to 50 ft/sec. A few are much larger, and yet more would have been larger if the analyses had not been split in the various ways already mentioned. This precision may prove disappointing to some people, but it appears to be what present data imply. The implications regarding the ballistic limits obtained by averaging are that those limits too are subject to substantial errors. This is particularly true for the many limits that were based on only a few rounds, and for those not selected by an over-under method.

Application of the Results

The early hope of the present project was that it would reach a simple, comprehensive correlation of the great mass of penetration data. This hope has not yet been realized because the great weight of the data has made progress slow. However, the objective is still there, and substantial progress seems to have been made toward achieving it. It is now possible to scan in 32 pages (Table 3), information which was contained at the start in about 15,000 pages of firing records, and the information has been processed according to fairly reasonable statistical procedures.

If and when further work of correlation is done, it should now be able to rest on firmer foundations, in that now a large collection of ballistic limits is available having associated measures of precision. Moreover, since the influence of projectile shattering seems so important, it should help to have at least the sketchy survey of breakage that is included in the table.

In view of many of the entries that can be found in Table 3, it is surprising that the earlier correlation work of Kilian, based on much the same data, was as successful as it was. Attention is called particularly to the many models of experimental shot that were used. Here many instances can be found where special variations of nose design or metallurgical design seemed to exert real influence on the ballistic limit, even though these results are rarely precise in the statistical sense. It should be noticed also that the last-resort analysis of citing simply the mixed zone was used most often for tests of experimental shot designs. Any over-all correlation of penetration data covering many designs of shot probably needs to be quite perceptive in its recognition of which kinds of shot may properly be grouped together.

In their present form, the results of the present survey of armor penetration data should be useful in that they provide a ready reference to a large body of information. Nevertheless, it is to be hoped that the further work of correlation and condensation will be continued.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Signifi-cance	of Rounds	(Abbreviations explained on p 27)
37	M74	0	1.00	324-385	899	SE = 22	66	SI
			1.12	265-363	1087	SE = 13	39	SI
			1.25	269-337	1209	SE = 7	60	SI
				230	1256	SE = 14		
			1.50	300	1381	SE = 6	545	SI
				370	1314	SE = 9		
			2.00	235-286	1685	SE = 13	94	SI, 84ARO
			2.25	235-293	1832	SE = 53	42	SI
			2.36	255	1880	2R(31)	3	60-mm armor, t 2.31
				230	2060	SE = 165		
			2.50	270	2091	SE = 81	27	SI&S
				310	2346	SE = 102		
				347	2591	HPP	5	SB&S, t 2.51
			3.00	255-347	2815	6R(179)	14	SI&S, t 3.03
		20	1.50	266	1789	LCP	7	SS, 842ARO
		25	2.00	258	1842	2R(29)	5	SI
		30	1.50	255	1617	6R(179)	7	SI&S
		40	1.50	255	1808	2R(28)	6	
		45	1.50	255	2212	2R(36)	6	SI&S
			2.50	251	2346	2R(51)	4	t 2.51
		50	2.50	269	2428	2R(44)	2	t 2.51
		55	2.50	251	2620	2R(48)	3	t 2.51
		60	1.00	341-375	2430	SE = 7	40	SB&S
			1.25	302	2720	SE = 6	25	SS
			2.50	269	2662	HPP	2	t 2.51
37	M80	20	1.00	--	--	--	0	73ARO
57/40		0	3.00	241	1898	2R(80)	4	SS
Tapered Bore			4.00	229	2308	2R(21)	6	SB&S
(Cf. OP5829/1)			10.00	205	4047	HPP	2	
		10	6.00	224	2669	HPP	1	SS
		30	3.00	241	2332	2R(18)	5	SB&S
			4.00	229	2738	6R(34)	8	SB&S
			6.00	224	Mix 3041 to 3463		12	SS
		45	3.00	241	3194	2R(36)	5	SB&S
			4.00	229	3313	6R(88)	11	SB&S, w/o PP at 3528
			6.00	224	Mix 2920 to 4022		10	SS
		55	3.00	241	4049	HPP	3	SS

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TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
57	M70	0	1.50	271-330	999	SE = 14	46	SI
			2.00	235-286	1248	SE = 9	35	SI
			2.25	235-293	1403	SE = 11	37	SI
				220	1454	SE = 36		
			2.50	280	1549	SE = 12	68	SI, 7ARO
				340	1470	SE = 30		
				220	1664	SE = 27		
			3.00	310	1817	SE = 12	210	SI
				400	1524	SE = 29		
				200	1964	SE = 48		
			4.00	280	2384	SE = 18	41	SI
				350	2154	SE = 27		
				388	2860	6R(124)	11	SS, t 4.02
			5.00	217-259	2867	6R(113)	10	SI, t 5.09, PP at 2418
		20	3.00	226	2204	2R(52)	2	SB, 3921ARO
			4.00	262	2992	HPP	6	SS, t 4.02
				357-388	2911	2R(24)	15	SS, t 4.01, lone PP
		25	4.00	388	2911	HPP	6	SS, t 4.02
				280	2813	SE = 24		
		30	3.00	340	2580	SE = 17	160	SS
				400	2429	SE = 23		
			4.00	388	2925	HPP	6	SS
				280	3015	SE = 71		
		35	3.00	340	2690	SE = 51	99	SS
				400	2514	SE = 35		
		40	2.00	291-300	1967	SE = 41	21	SB
				220	2116	SE = 177		
			2.50	290	2624	SE = 128	87	SI&S
				360	2413	SE = 106		
				320	2987	SE = 41		
			3.00	360	2671	SE = 19	78	SS
				400	2618	SE = 23		
		45	3.00	262	1734	2R(31)	5	t 3.12
		50	1.50	330	2094	SE = 27	13	SI&S
				280	2358	4R(40)	10	SB
			2.00	320	2420	SE = 22	25	SS
				360	2312	SE = 23	46	SS
				220	2671	SE = 40		
			2.50	290	2780	SE = 43	63	SS
				360	2703	SE = 27		

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TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot: Cal, mm	Shot: Model No.	Nom. Obl., deg	Plate: Nom. t, in.	Plate: BHN, kg/mm²	Ballistic Limit: BL(A), ft/sec	Ballistic Limit: Significance	Number of Rounds	Notes (Abbreviations explained on p 27)
57	M70	55	2.00	290-291	2494	SE = 38	14	SB
			2.50	327-353	2941	SE = 60	20	SS
		60	1.25	273-352	2375	SE = 67	35	SI&B
			1.50	331	2412	6R(92)	10	t 1.49, SB&S
			2.00	289-302	2785	SE = 17	21	SB
			2.50	327	2939	HPP	6	SS
		70	1.25	273-341	2907	SE = 41	35	SI&B
75	M72	0	1.50	255	737	2R(28)	7	SI
			2.00	235-286	924	SE = 13	54	SI
			2.25	223-293	1048	SE = 7	37	SI
				230	1120	SE = 26		
			2.50	290	1149	SE = 14	55	SI
				350	962	SE = 38		
			2.75	252	1241	2R(24)	3	t 2.73, 6ARO
				220	1311	SE = 15		
			3.00	310	1367	SE = 14	79	SI
				400	1263	SE = 30		
			3.50	262-289	1536	4R(84)	6	t 3.49
				200	1570	SE = 33		
			4.00	260	1711	SE = 10	41	SI&S, 11ARO
				320	1655	SE = 25		
			5.00	217-217	1995	6R(147)	7	SI
		20	3.00	246-262	1634	LCP	11	SI&B, 2744ARO
			4.00	300	2582	2R(43)	3	SB, t 3.96
		25	2.00	255-258	972	2R(35)	10	SI
		30	1.50	255	790	2R(52)	6	SB&S
			3.00	298	2086	2R(41)	6	SB&S
			4.00	--	2595	4R(42)	7	SS
		35	1.50	255	1088	LCP	3	SI
		40	1.50	255	1013	2R(36)	2	
		45	1.50	255	1210	2R(35)	4	SI
			2.25	258	2092	LCP	3	
			2.50	289	2118	HPP	2	SS, t 2.51
			3.00	300	2385	2R(52)	4	SS, t 3.01
		50	2.00	262	2001	2R(2)	2	SI
		55	2.00	262	1996	HPP	1	
		60	1.50	265-285	1867	4R(121)	11	SB
			2.00	262-300	2395	SE = 44	17	SS

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
75	T43	20	5.00	225	2147	4R(56)	[illegible]	SB&S, t 5.02
		55	3.38	253	2920	4R(85)	7	SS
75	T148 (11 exp. lots[a])	0	2.00	277-285	Mix 842 to 1191		19	T148, 4 lots, SB
				285	Mix 1047 to 1648		12	M72 mod, 3 lots, SB
		30	3.00	262-298	Mix 1859 to 2215		12	T148, 3 lots, SI&B
		45	2.00	293	1406	2R(21)	6	T148, 1 lot, SI
				293	1518	2R(84)	4	M72 mod, 1 lot, SI&B
			2.50	269	Mix 1620 to 1800		6	T148, 1 lot, SI&B
		55	2.50	269	2136	2R(3)	2	T148, 2 lots, SI&B
			3.00	262	2198	HPP	2	T148, 1 lot, SI
		60	1.50	265-285	Mix 1194 to 1414		15	T148, 3 lots, SI
			2.00	277-400	Mix 1437 to 1965		42	T148, 8 lots, SI&B
				262-293	1700HPP, 2105LCP		7	M72 mod, 2 lots, SI&B
			2.50	269	2210	2R(28)	7	T148, 3 lots, SI&B
75	T149[b]	20	4.00	300-308	2641	6R(132)	16	R_C61, t 3.97, SB&S
				300	2619	6R(102)	10	R_C55, t 3.96, SB&S
				308	2590	4R(144)	6	R_C61, w/tip
		45	3.00	300	2403	2R(34)	3	R_C61, t 3.01, SB
				300	2389	6R(58)	9	R_C55, t 3.01, SS
		55	3.00	302	2632	4R(98)	9	R_C61
				302	2306	LCP	4	R_C61, w/tip
				302	2427	HPP	3	R_C61, w/o tip
		60	2.00	300-321	2582	4R(82)	9	R_C61
				300	2366	6R(36)	10	R_C55, SS
				321	2080	2R(33)	4	R_C61, w/tip
				291-321	2025	4R(118)	9	R_C61, w/o tip

(a) The great majority of these tests with the T148 shot were performed under Project TA1-1251. This project used three varieties of M72 shot with its tip cut off, and six varieties of M72 shot which were first softened, then had their tips cut off, and were rehardened. These six varieties, differing in windshield and heat-treatment, were designated T148. Since the reference report says no variety showed clear superiority, all are lumped together here. Included also are two lots used in Project TA1-1301. For more details, see Report 2 on Project TA1-1251.

(b) The tests with the T149 were part of Project TA1-1254. Shot were used with Rockwell C hardness either 61 or 55. In addition, those here marked w/tip were truncated, then had the tips reattached. Those marked w/o tip were truncated, but the tips were not replaced.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal., mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
76	M79	0	2.25	223	991	2R(36)	3	SI, t 2.24
			2.50	229-341	1089	SE = 15	17	SI
			3.00	251-363	1336	SE = 11	25	SI
				200	1578	SE = 64		
			4.00	260	1640	SE = 70	18	SI
				320	1762	SE = 48		
			5.00	212-269	Mix 1932 to 2234		9	SI
				311	2577	HPP	5	SS
		10	3.00	363	1424	HPP	1	SS, t 3.03
		20	2.25	223	1020	2R(27)	5	SI, t 2.24
			3.00	302	1782	2R(41)	11	SI, t 3.05 (937ARO)
				363	1901	4R(100)	8	SS, t 3.03 (937ARO)
		30	2.25	223	1196	2R(20)	5	SI, t 2.24
				230	1315	SE = 51		
			2.50	310	1694	SE = 40	32	SI&S
				390	1750	SE = 63		
			3.00	302	2065	2R(24)	6	SS, t 3.05
				363	1927	4R(93)	7	SS, t 3.03
			4.00	207-302	2532	SE = 34	14	SB&S
		40	2.25	223-293	1852	SE = 37	16	SB&S
			3.00	331	2246	4R(74)	7	SS, t 3.05
				379	2012	2R(24)	7	SS, t 3.05
				230	2004	SE small		
		45	2.50	310	2057	SE small	21	SB&S. Parabola fitted w/o overlapping by PP's or CP's.
				390	1963	SE small		
			3.00	331	2356	4R(92)	6	SS, t 3.05
		50	2.25	269-293	2032	4R(56)	9	SS, t 2.28
			3 00	379	2369	4R(95)	5	SS, t 3.05
		55	3.00	260	2876	2R(36)	3	SB&S
		60	2.00	306	2178	4R(32)	6	SS
				230	2626	SE = 12		
			2.50	290	2520	SE = 10	26	SS
				340	2443	SE = 18		
			3.00	295	2838	2R(3)	3	SB

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
76	T128E6 (M339)	0	3.00	298	1517	6R(43)	15	SI
				298	1987	6R(133)	9	SB&S
			4.00	260	2049	SE = 34	16	SI&B
			5.00	260	2221	2R(8)	8	SI, t 5.13
		20	4.00	260	Mix 2088 to 2565		13	SB&S
			5.00	260	2443	2R(39)	5	SB&S, t 5.13
		30	2.00	290	1358	SE = 43	10	SI
			2.50	291	1696	SE = 101	13	SB&S
			3.00	298	2519	6R(113)	16	SB&S, t 2.99
			4.00	250	2832	4R(95)	7	SB, t 4.07
			5.00	250	3179	HPP	4	
		45	2.00	290	1934	6R(151)	8	SB, t 2.04
			2.50	291	2266	6R(81)	9	SB&S, t 2.52
			3.00	298	2718	6R(127)	7	SB, t 2.99
			4.00	260	3206	4R(61)	8	SB, t 4.07
		55	3.00	302	2506	2R(55)	5	SB
		60	2.00	290-291	2481	SE = 15	15	SB&S
			2.50	291	2857	6R(135)	9	SB, t 2.52
			3.00	298	3108	4R(67)	7	SB, t 2.99
		65	2.00	290	2830	4R(64)	9	SB&S, t 2.04
			2.50	291	3112	6R(155)	8	SB&S, t 2.52
		75	2.00	290	3253	HPP	4	SB, t 2.02
76	T166[a]	30	4.00	--	2302	4R(73)	8	E2, R$_C$66, w/o WS, SS
				--	2653	4R(77)	9	E2, R$_C$62, w/o WS, SS
				--	2382	2R(69)	8	E2, R$_C$57, w/o WS, SS
		55	3.00	298	2640HPP,	2822LCP	4	E1, SB&S, BL(P) = 2846
				250	2554	4R(94)	7	E2, R$_C$62, w/WS
				302	2841	4R(103)	9	E2, w/o tip or WS, SB
				250	2552	2R(46)	3	E3, SB
				260	2586	2R(61)	4	E4, SI&B
				298	2572	4R(66)	6	E5, SB

(a) The tests with the T166 are from Project TA1-1301. The T166 shot is essentially the T128E6 (or M339) shot with its tip first removed then reattached by cementing or welding. The various modifications, E1 to E5, refer to slight changes in the geometry of the ogive and tip. Modification E2, which was the preferred one, also was tested with or without the tip and/or windshield, and at various Rockwell C hardnesses at the bourrelet.

Probit analyses applied to all the T166 data for the first five combinations of obliquity and plate thickness give the following results, respectively: BL = 2703, SE = 58; BL = 2661, SE = 53; BL = 1901, SE = 46; BL = 2543, SE = 34; BL = 2933, SE = 61. These results illustrate the effects of grouping slightly divergent data.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
76	T166	60	2.00	288	1714	LCP	2	E1, SI
				289	2027	2R(58)	5	E2, R_C66, w/o WS, SB
				291	1901	6R(152)	9	E2, w/o tip or WS, SI&B
				289	2048	2R(51)	4	E2, R_C57, w/o WS
				306	2047	LCP	5	E4, SI&B
				306	1940	2R(67)	6	E5, SI&S
			2.50	306	2618	2R(1)	8	E2, R_C62, w/WS, SI&B
				306	2514	2R(85)	7	E4, SI&B
				306	2573	4R(142)	6	E5, SB
			3.00	260	2977	HPP	4	E2, R_C62, w/WS, SI&S
				260	2916	HPP	1	E4, SS
				295	2880	2R(37)	8	E5, SB
		70	2.00	291	2903	HPP	5	E2, w/o tip or WS, SB
90	M77	0	2.50	252	1281	LCP	5	SI
			3.50	262-289	1550	LCP	3	
				200	1537	SE = 46		
			4.00	260	1643	SE = 24	37	SI, 4 shattered
				320	1545	SE = 40		
			5.00	217-274	Mix 1804 to 2527		44	SI&S
			8.00	220	3204	HPP	2	SI, t 7.94
		10	8.00	220	3430	HPP	2	SS, t 7.94
		20	2.50	255	1254	LCP	3	SI
			3.00	--	--	--	0	229ARO
			5.00	220-228	Mix 1996 to 2885		33	SB&S
			6.00	270-275	3146	HPP	10	SS
		30	2.50	229-311	1234	SE = 18	20	SI
			4.00	207-269	2334	SE = 25	12	SB&S
			5.00	220	2703	4R(119)	5	SB, t 5.15
					2938	2R(75)	5	SS, t 5.10
			6.00	220	3220	HPP	3	SS
		35	2.50	255	1489	4R(63)	9	SI&B
				230	1803	SE = 24		
		45	2.50	290	1843	SE = 20	38	SB&S
				350	1775	SE = 29		
			4.00	207-269	2614	6R(81)	10	SB
			5.00	220-224	3101	4R(105)	13	SS, t 4.97
		55	2.50	252-255	203[illegible]	SE = 18	12	SS
			3.00	285	2429	4R(24)	8	SB&S, t 2.99
			3.38	230-266	2642	SE = 34	43	SS
		60	2.00	2[illegible]4	214[illegible]	4R(75)	8	SS
				230	2323	SE small		
			2.50	300	243[illegible]	SE small	23	SS, [illegible]abola fitted with almost no overlap by PP's or CP's.
				370	2483	SE small		

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	T33	0	2.50	229-364	1495	LCP	9	SI
(misc. models,			4.00	210-300	1558	6R(119)	16	SI
other than E7)				326	1307	LCP	5	SI
			5.00	200-311	1873	SE = 14	31	SI
			6.00	265	2150	SE = 114	14	SI&B
			8.00	220	3234	HPP	2	SS
		20	5.00	220-228	2008	SE = 53	271	SI&S, acceptance tests
		30	4.00	220-280	1939	SE = 29	24	SI&S
			5.00	220-225	2852	4R(51)	9	SB&S, t5.11
			6.00	220	3244	HPP	3	SS, t6.06
		40	3.00	280	1880	6R(57)	13	SB, t3.02
		45	3.00	262	2000	2R(20)	10	SS, one PP at 2073
			5.00	225	3198	2R(97)	2	SS, t5.08
		55	3.00	280-302	2370	SE = 50	25	SB
				285	2291	6R(148)	7	w/boom and tail
			3.38	230-263	2683	SE = 11	302	SS, acceptance tests
			4.00	282-294	3004	SE = 38	12	
		60	3.00	273-311	2613	SE = 17	56	SB
90	T33E7	0	5.00	259	1962	2R(113)	8	SI, t5.10
(not part of Project AX23)			6.00	256	2302	2R(5)	6	SI, t5.96
		20	6.00	243	2418	2R(7)	8	SI&B, t6.07
		30	4.00	308	2135	SE = 41	35	
		55	3.00	243-311	2371	SE = 30	88	77 ARO
			4.00	234	3026	4R(95)	6	
		60	3.00	29[illegible]	2730	SE = 57	18	
90	T33E7	20	5.00	277	2473	LCP	11	LR, R_C62, t4.99
(Project AX23)[a]				277	2093	4R(80)	8	LR′ R_C62 SB
					PP2626 to 2749		20	LR′ R_C62, shatter gap
				277	2752	LCP	1	L11, R_C56 SS, t4.99

(a) Project AX23 was a test of steel for the shot T33E7, with various lots differing metallurgically. The Rockwell C hardness of the different lots is shown here briefly. For example, R_C62 means hardness 62. Other metallurgical features can be found in Project AX23 reports by noting the lot numbers. Here LR and LR′ denote the reference lot, with and without windshield; L1 to L10 denote Lots FA-PD-1 to FA-PD-10; and L11 denotes the lot made from FS-4160 steel.

In Project AX23, tests at obliquity 20 and 25 degrees were carried to velocities well above the low ballistic limits, in an effort to find velocity ranges where projectile shattering might produce partial penetrations. This accounts for the multiple entries shown here for some ballistic limits.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	T33E7 (Project AX23, continued)	20	6.00	269-280	Mix 2495 to 3155		51	LR, R_C62, SB&S, t6.04
				270	2472	2R(27)	14	L5, R_C62, SI&S, t6.03
				262-280	2506	4R(86)	6	L1, R_C61, SI&B, t6.02
					Mix 2944 to 3118		16	L1, R_C61, shatter PP's
				276-280	2530	4R(69)	6	L2, R_C61, SI&B, t6.07
					Mix 2982 to 3149		13	L2, R_C61, shatter PP's
				262-270	2519	2R(72)	7	L6, R_C60, SI, t6.02
					Mix 2934 to 3118		9	L6, R_C60, shatter PP's
				269-276	Mix 2531 to 3389		27	L8, R_C60, SB&S, t6.04
				269-276	3158	HPP	18	L10, R_C60, SS, t6.03
				269-276	2554	6R(162)	8	L7, R_C58, SI, t6.03
					2909	LCP	16	L7, R_C58, shattered
				269-275	3092	4R(82)	14	L3, R_C55, SB&S, t6.07
				270-280	3128	2R(95)	14	L4, R_C52, SS, t6.04 One CP(A), no CP(P)
				262-276	3124	2R(73)	12	L9, R_C50, SS, t6.04 One CP(A), no CP(P)
		25	5.00	277	2206	2R(15)	3	LR, R_C62, SB&S, t4.99
					CP 2311 to 3041		10	LR, R_C62, SB&S, t4.99
				277	2891	LCP	1	LR', R_C62, SB, t4.99
		30	4.00	299-300	Mix 1984 to 2584		28	LR', R_C62, SB&S, t3.98
			5.00	277	2825	2R(78)	8	LR, R_C62, SS, t4.98
				277	2855	2R(22)	7	L1, R_C61, SS, t4.98
				277	2944	2R(16)	3	L4, R_C52, SS, t4.98
		55	3.00	299-301	2507	SE = 15	29	LR, R_C62, SB&S
				300	2511	6R(100)	11	LR', R_C62, SS
				299	2510	6R(47)	8	L5, R_C62, SB&S, t3.02
				299	2457	4R(59)	7	L1, R_C61, SB&S, t3.01
				299	2490	4R(35)	6	L2, R_C61, SS
				299	2589	6R(119)	8	L6, R_C60, SS, t3.02
				302	2489	4R(77)	9	L8, R_C60, SS
				285	2515	6R(68)	8	L10, R_C60, SB&S, t2.99
				302	2512	2R(27)	7	L7, R_C58, SS, t2.99
				299	2449	4R(19)	6	L11, R_C56, SS
				299	2518	6R(63)	7	L3, R_C55, SS
				299	2441	6R(118)	7	L4, R_C52, SS
				285	2537	6R(82)	10	L9, R_C50, SS, t2.99
			4.00	299	3160	2R(34)	13	LR', R_C62, SS
		60	2.00	289	2428	6R(114)	8	L2, R_C61, SS, t2.01
				294	2439	2R(66)	6	L7, R_C58, SB&S
				289	2138	6R(84)	15	L4, R_C52, SB&S, t2.01 One CP(A) [illegible]
			1.00	299	[illegible]	5R(114)	10	LR', R_C62, SB&S

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	T43	55	3.00	302	2398	6R(22)	10	
			4.00	210-326	2990	6R(116)	13	SS
90	T54E1	0	7.60	258-297	3205	HPP	7	SB&S, t 7.65
		30	4.00	292	2068	6R(55)	10	SI&S, t 4.01
			5.00	245-347	2982	SE = 61	33	SB&S
			6.00	249-296	3223	HPP	19	SS, t 5.99
			7.60	258	3180	HPP	4	SS, t 7.65
		45	4.00	295	2553	SE = 38	15	SS
			5.00	245-337	3205	SE = 23	31	SB&S
			6.00	297	3121	HPP	5	SS, t 6.02
		55	4.00	297-315	2847	SE = 53	26	SS
		60	2.00	285	2428	64(41)	10	SB, t 2.03
			3.00	260	2651	SE = 31	41	SS
				320	2691	SE = 18		
				390	2337	SE = 20		
			4.00	280	3182	SE = 78	41	SS
				340	3064	SE = 42		
				380	2995	SE = 39		
		65	3.00	256-306	3034	SE = 52	20	SS
		70	2.00	296	2860	4R(118)	9	SS
			3.00	307-381	3177	SE = 27	25	SS
105	T182	55	5.00	280-285	Mix 3040 to 3430		38	SI&B
(E2, E3, E4, E5)		60	4.00	248-300	Mix 2951 to 3218		20	

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 1. Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
120	T116	0	10.00	239	3298	6R(103)	8	E5, SB, t10.14
(Mods E4, E5)		20	7.60	248	2464	2R(21)	7	E5, SB, t7.55
			8.00	240	3344	2R(70)	6	E5, SB
		30	6.00	241	2302	6R(68)	8	E5, SB&S, t6.07
		45	4.00	297	1978	2R(42)	7	E4, SB, t4.02
			5.00	291	2243	6R(142)	10	E4, SB
				267-287	2615	SE = 27	17	E5, SB
			7.60	260	3369	HPP	3	E5, SB, t7.53
		50	5.00	259	2817	6R(105)	9	E5, SS, t5.09
			6.00	247	3127	HPP	2	E4, SB, t5.99
		55	4.00	262	2514	4R(55)	7	E5, SS, t3.96
			5.00	267-287	2942	SE = 72	16	E5, SB
		60	2.00	283	1752	6R(87)	8	E5, SI&S, t2.02
			3.00	285	2353	4R(79)	7	E4 w/o WS, SS, t3.01
			4.00	297	2465	6R(105)	11	E4, SB, t4.03
				255	2830	4R(58)	6	E5, SB, t4.02
			5.00	293	2872	4R(93)	6	E4 w/o WS, SS
		65	2.00	277	2070	LCP	6	E5, SB, t2.02, BL(P) = 2116, 6R(96)
			3.00	293	2564	6R(111)	6	E5, SB, t3.04
			4.00	294	3064	2R(57)	6	E4 w/o WS, SS, t4.06
				255	3106	LCP	6	E5, SB&S, t4.02, BL(P) = 3176, 6R(124)
		70	2.00	285	2282	6R(84)	6	E5, SS, t2.02
			3.00	285	2962	4R(76)	5	E4 w/o WS, SS, t3.01
		75	2.00	294	2681	2R(18)	6	E5, SB, t2.03
			3.00	303	3296	HPP	4	E5, SB, t2.97
155	M112	0	5.00	250-274	1414	2R(41)	10	SI, t5.04
		15	[illegible]	250	1642	LCP	4	SI, t5.04, BL(P) = [illegible], 2R([illegible])
		30	4.00	210	1162	SE = [illegible]	45	SI
				270	1385	SE = 43		SI
				3[illegible]0	1545	SE = [illegible]		SI&S
			5.00	[illegible]-242	1643	LCP	[illegible]	SI
				250-269	1932	[illegible]R(115)	[illegible]	SI
				30[illegible]-311	2058	2R(17)	10	SI&S
			6.00	265	2026	LCP	4	t6.0[illegible]
		45	[illegible]	200-274	2493	6R(101)	11	SB&S, t5.03
				[illegible]-316	2101	2R(6)	[illegible]	SB&S, [illegible]
6 in.	Mk XXVII	15	5.00	255	[illegible]	LCP	3	SI, t5.0[illegible], BL(P) = [illegible], 2R( )

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
				240	1199	SE = 15		
37	M51	0	1.00	320	1211	SE = 10	39	SI, 9ARO
				400	891	SE = 13		
				240	1189	SE = 25		
			1.12	310	1260	SE = 14	60	SI
				380	1148	SE = 32		
			1.25	302	1455	4R(93)	4	SI
				230	1564	SE = 14		
			1.50	300	1630	SE = 7	67	
				370	1641	SE = 13		
			2.00	302-306	1949	4R(61)	6	8ARO
			2.25	282	2304	2R(42)	3	t2.36
				220	2226	SE = 15		
			2.50	280	2348	SE = 9	23	
				340	2517	SE = 11		
			3.00	281-288	2604	6R(155)	6	SI&S
		10	1.12	302-321	1324	4R(83)	8	SI, t1.13
				250	1260	SE = 14		
		20	1.00	320	1276	SE = 12	35	SI
				400	1062	SE = 20		
			1.12	302-321	1377	6R(56)	12	SI, t1.13
			1.25	302	1501	4R(76)	4	SI
				230	1634	SE = 16		
			1.50	300	1730	SE = 12	45	
				370	1774	SE = 16		
		25	1.00	324-385	1223	4R(88)	8	SI, 9ARO
				240	1409	SE = 17		
		30	1.00	320	1397	SE = 11	34	SI
				400	1396	SE = 16		
			1.12	302-326	1563	SE = 41	17	SI
			1.25	241-302	1614	6R(122)	13	SI, t1.26
				220	1859	SE = 28		
			1.50	300	1902	SE = 16	48	
				370	2133	SE = 20		
		35	1.00	341-375	1598	SE = 14	41	SI&S
			1.25	302	1791	SE = 20	20	SI&S
				240	1644	SE = 23		Data from AD 686,
		40	1.00	320	1756	SE = 17	53	SI for BHN ≤ 321,
				400	1779	SE = 22		SI&S for BHN ≥ 341
				365	2156	2R(31)	9	Data from AD 1084,
				388-402	2110	6R(140)	13	shot breakage in doubt,
				429	2006	2R(22)	4	compare with AD 686
				240	1706	SE = 60		
			1.12	310	1853	SE = 30	60	SI
				380	1806	SE = 67		

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
37	M51	40	1.25	241-255	1853	6R(133)	6	SI, t 1.27
				311	2060	6R(124)	9	SI, t 1.23
				230	2186	SE = 21		Data from AD 679, SI for BHN ≤ 302, SI&B for BHN ≥ 346
			1.50	300	2311	SE = 19	58	
				370	2653	SE = 21		
				302-364	3033	HPP	15	SB. Data from AD 1084. Compare with AD 679
				375	2794	2R(73)	3	
				240	2457	SE = 41		
		45	1.50	290	2649	SE = 31	40	
				340	2875	SE = 73		
				240	2183	SE = 56		Data from AD 686 and AD 1084, SI for BHN ≤ 321, SI&S for BHN ≥ 341
		50	1.00	320	2242	SE = 30	86	
				400	2060	SE = 31		
				240	2139	SE = 65		
			1.12	310	2395	SE = 40	66	SI&B
				390	2433	SE = 80		
				241	2360	4R(144)	10	SI. Low precision BL
			1.25	255-269	2498	6R(72)	15	SI
				311	2812	2R(61)	9	SB, t 1.23
			1.50	229-255	2770	SE = 59	25	SI, t 1.51
				266-375	2822	HPP	9	SI, t 1.51
57	M86	0	1.25	302	1048	4R(79)	4	SI
				240	1292	SE = 22		
			1.50	300	1227	SE = 23	56	
				360	799	SE = 21		
			2.00	255	1743	2R(46)	3	SI, t 1.99
				230	1864	SE = 13		
			2.50	290	1780	SE = 8	21	SI
				350	1702	SE = 23		
				260	2112	SE = 17		SI for BHN ≤ 347, SB&S for BHN ≥ 408
			3.00	330	1983	SE = 15	20	
				400	1879	SE = 16		
				210	2417	SE = 154		SI for BHN ≤ 269, SI&B for BHN ≥ 321
			4.00	300	2545	SE = 97	45	
				390	2402	SE = 107		
		20	1.25	302	1109	2R(54)	3	SI
				240	1323	SE = 19		
			1.50	300	1372	SE = 15	29	SI
				360	1141	SE = 16		
				260	2164	SE small		SI. Parabola fitted with overlapping [illegible]
			3.00	330	2116	SE small	20	
				400	2119	SE small		

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
57	M86	20	4.00	220	2503	6R(148)	10	SI
				357-388	2807	HPP	10	SB&S, t 4.01
		25	3.00	347	2397	2R(26)	4	SI&B, t 3.04
			4.00	388	2755	HPP	4	SS, t 4.02
		30	1.25	302	1264	2R(20)	4	SI
				240	1432	SE = 19		
			1.50	300	1470	SE = 15	31	SI
				360	1359	SE = 18		
			2.00	258-277	1755	SE = 10	15	SI
				220	1826	SE = 60		SI for BHN $\leq$ 311
			2.50	290	2116	SE = 31	24	SB&S for BHN $\geq$ 341
				360	2153	SE = 36		
				260	2278	SE = 50		SI&B for BHN $\leq$ 320
			3.00	330	2648	SE = 27	167	SS for BHN = 370
				400	2613	SE = 43		SI&S for BHN = 400
			4.00	220	2550	HPP	2	SI
				388	2757	HPP	4	SS, t 4.02
				261-289	2732	SE = 111	52	SI&B
		35	3.00	298-320	Mix 2501 to 2792		105	SI&S, probit diverges
				347-360	PP2516 to 2812		26	SS, lone CP at 2743
				400-408	2724	SE = 10[illegible]	32	SS
		40	1.25	277-302	1465	6R(6[illegible])	7	SI
				230	1675	SE = 16		
			1.50	300	1646	SE = 10	25	SI
				360	1707	SE = 12		
			2.00	241-285	1[illegible]77	SE = 7	18	SI. Parabolic probit
				300	2128	SE = 23	17	did not converge
				220	2181	SE = 6[illegible]		SI for BHN $\leq$ 277
			2.50	290	24[illegible]6	SE = 2[illegible]	82	SI&S for BHN $\geq$ 311
				360	26[illegible]5	SE = 30		
				280	272[illegible]	HPP	7	SI&S
			3.00	360	277[illegible]	HPP	6	SS
				400	271[illegible]	2R(12)	10	SS
		45	1.50	255-2[illegible]	183[illegible]	SE = 30	16	
			2.00	285	2303	SE = 24	11	SI
			2.50	360	26[illegible]5	HPP	[illegible]	SI&S, t 2.4[illegible]
		50	1.25	262-302	1[illegible]2[illegible]	6R(85)		SI
				230	1[illegible]53	SE = 25		SI for BHN $\leq$ 33[illegible]
			1.50	300	204[illegible]	SE = 13	7[illegible]	SI&B for BHN $\geq$ 332
				370	2022	SE = 1[illegible]		
				240	2525	SE = 15[illegible]		SI for BHN $\leq$ 2[illegible]5
			2.00	300	2735	SE = [illegible]	[illegible]6	SI&S for BHN $\geq$ 3[illegible]
				360	2621	SE = [illegible]		
			2.50	22[illegible]-320	26[illegible]	HPP	11	SI&S, t [illegible]4

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
57	M86	55	1.50	269	2341	2R(48)	5	t 1.48
			2.00	285-302	PP 2585 to 2712		15	SI, lone CP at 2691
			2.50	353	2705	HPP	5	SB, t 2.51
		60	1.25	273-352	2179	SE = 28	30	SI
				230	2468	SE = 46		
			1.50	300	2634	SE = 33	53	SI
				360	2592	SE = 48		
		65	1.25	316-352	2504	SE = 24	23	SI&B
		70	1.25	277-341	PP 2573 to 2710		21	SI, lone CP at 2664
75	M61	0	1.50	287	952	HPP	1	
			2.25	282	1175	2R(64)	8	SI, t 2.36, one PP
			4.00	202	1596	2R(41)	3	SI, t 3.98
				273	1755	2R(34)	3	SI, t 3.98
		20	2.25	282	1548	2R(57)	5	SI, t 2.36
			3.00	262	1971	2R(36)	3	SI, 1489ARO
		25	1.50	267-287	958	SE = 4	17	SI
		30	5.00	224	3175	HPP	3	SI&S, t 5.12
		45	2.50	269	2097	HPP	1	SS, t 2.51
		60	1.50	265-285	2047	2R(6)	4	
			2.00	282	2095	HPP	2	
				400	1782	LCP	1	
75	T42	20	5.00	225	2324	4R(59)	4	SS
		55	3.38	253	2329	HPP	2	SS, t 3.44
76	M62	0	2.25	223-293	1348	SE = 5	24	SI
				230	1420	SE = 29		
			2.50	290	1375	SE = 21	26	SI
				340	947	SE = 26		
				300	1503	SE = 51		
			3.00	350	1330	SE = 43	23	SI
				400	1206	SE = 31		
			4.00	204-326	1987	SE = 38	26	SI, one CP at 1787
		20	2.25	223-293	1446	SE = 15	[illegible]	SI
			3.00	302-348	1729	[illegible](153)	[illegible]	SI, 214ARO
				240	[illegible]	SE = 50		SI for BHN ≤ 273
			4.00	280	2377	SE = [illegible]	[illegible]	SB&S for BHN ≥ 302
				320	2516	SE = 47		21ARO
		25	2.25	286	1476	[illegible](83)	6	SI

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TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal., mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
76	M62	30	2.00	235-277	1472	SE = 16	13	SI
			2.25	223-293	1500	SE = 22	23	SI
				230	1627	SE = 43		
			2.50	290	1672	SE = 26	23	SI
				340	1558	SE = 38		
				220	1534	SE = 181		
			3.00	310	1935	SE = 89	34	SI&S
				410	2285	SE = 255		
			4.00	202-273	2333	6R(169)	13	SI
				244-302	2674	6R(74)	14	SB&S (shatter gap)
		40	2.00	235-269	1861	SE = 48	13	SI&B
			2.25	223-293	1772	SE = 59	27	SI
				220	2146	SE = 77		
			3.00	310	2437	SE = 43	36	SS
				400	2211	SE = 51		
				230	1438	SE = 59		
		45	1.50	300	1460	SE = 28	52	SI
				370	1408	SE = 29		
			2.00	235-269	1789	SE = 19	19	SI
			2.25	258	2079	6R(99)	9	
			2.36	255	1983	6R(98)	11	t 2.31
				230	2014	SE = 118		
			2.50	310	2280	SE = 76	47	SI&B
				390	2287	SE = 122		
			3.00	259	2440	HPP	1	SS
		50	2.00	248	2082	2R(61)	3	SI
			2.25	223-293	2309	SE = 56	30	SI
		55	2.25	258	2664	2R(78)	3	
			2.36	255	Mix 2437 to 2684		8	t 2.31
			2.50	229	2592	HPP	1	SI
				230	2114	SE = 57		
		60	1.50	300	2200	SE = 31	45	SI
				370	2082	SE = 37		
			2.00	235-277	2640	4R(100)	11	SI, t 1.99
			2.25	248	2649	HPP	2	
			2.50	229-341	2662	HPP	5	SI, t 2.51
90	M82	0	2.50	252	1310	2R(115)	7	SI
			3.00	229	Mix 1611 to 1704		7	SI
			3.50	262-289	1390	LCP	2	
				200	1794	SE = 107		
			4.00	260	2030	SE = 66	19	SI
				320	1713	SE = 87		
			5.00	274	2334	2R(32)	5	t 5.07
			8.00	220	3236	HPP	2	SB, t 7.34

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TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	M82	10	6.00	236	2592	2R(45)	11	SI
			8.00	209	3115	LCP	2	SI, HPP(P) = 3145, t 7.94
		20	2.50	255	1418	2R(36)	4	SI
			3.00	229-285	1612	6R(95)	9	t 3.01
			4.00	204-326	2019	SE = 37	28	SI
			5.00	220-232	2442	SE = 15	42	SI&B
				230	1569	SE small		SI. Parabola fitted
		30	2.50	280	1487	SE small	17	with almost no overlap by PP's or CP's
				340	1433	SE small		
				220	1818	SE = 15		
			3.00	280	1778	SE = 1[illegible]	48	
				340	1744	SE = 17		
				200	1916	SE = 157		
			4.00	260	2253	SE = 68	52	SI
				320	2500	SE = 170		
			5.00	200-300	2654	SE = 48	53	SI
			6.00	220	3041	2R(62)	3	SE, t 6.03
		35	2.50	255	1720	6R(127)	8	SI
			3.00	226-293	1854	6R(63)	12	t 2.98
		40	3.00	235	2050	LCP	4	SI&B
			4.00	223	2711	4R(142)	6	SI
		45	2.36	255	1930	2R(63)	3	t 2.31
				220	1975	SE = 61		
			2.50	290	2075	SE = 35	41	SI&S
				360	1936	SE = 45		
				230	2185	SE = 35		
			3.00	280	2393	SE = 21	201	SI&S
				340	2357	SE = 60		
			4.00	202-204	2617	6R(149)	7	SI, t 3.97
				244-273	2820	HPP	4	SI&S, t 3.98
			5.00	220-224	3184	4R(95)	8	SI&S, t 5.02
		50	2.25	258	Mix 1893 to 2231		7	
			2.50	269	2386	2R(27)	4	SS, t 2.51
			3.00	226-289	2592	SE = 56	16	
		55	2.36	255	2421	2R(61)	3	t 2.31
			2.50	255-269	2607	SE = 25	13	SI
			3.00	269	2786	HPP	2	
			3.38	243-263	3231	6R(137)	11	SI&S, t 3.45
		60	2.25	258	2564	LCP	3	CP(N) at 2564
			2.50	229-311	2840	4R(84)	11	SI&S, t 2.53

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	T25	20	5.00	220	2314	2R(39)	7	SI&B, t 5.03
	T26	20	5.00	220	Mix 2174 to 2322		8	SI&S, t 5.04
	T27	20	5.00	220	2421	6R(88)	8	SB&S, t 5.04
	T28	20	5.00	220	2366	4R(124)	7	SI&S, t 5.03
90	T39	30	5.00	220-223	Mix 2196 to 2585		58	SI&S, 13 special lots
		45	3.00	262	2253	6R(74)	13	SS, 1 lot
			5.00	220-223	3061	SE = 74	27	SI&S, 5 special lots
		55	3.00	280-320	2735	SE = 68	83	SS, 1 lot
			3.38	263-270	2965	SE = 166	45	SS, 8 special lots
		60	2.00	285	2373	4R(62)	9	SB, t 2.03, 1 lot
90	T50(a)	45	5.00	220-224	2990	SE = 19	55	SI&S, 8 special lots
		55	3.38	243-260	Mix 2811 to 3251		46	SB&S, 8 special lots
90	T50E1	0	5.00	259	2176	6R(90)	8	SI, t 5.10
			6.00	256	2385	4R(90)	9	SI, t 5.96
			7.60	258-297	2845	SE = 21	21	SI
		20	6.00	248	2562	2R(40)	7	SI&B, t 6.07
			8.00	240	3280	HPP	4	SB
		30	3.00	291	1731	6R(103)	12	SS
			4.00	230-292	2154	SE = 5	22	SI
			5.00	240	2308	SE = 19	30	SI
				290	2578	SE = 34		
				340	2462	SE = 18		
			6.00	297	2904	6R(124)	10	SI&B, t 6.02
			7.60	297	3214	HPP	10	SI&B, t 7.47
		40	6.00	256	3193	6R(48)	6	SS, t 5.96
		45	4.00	262	2457	6R(120)	8	SS
				245	2874	6R(161)	4	SS
			5.00	245	2964	4R(46)	10	SI
				275-337	3182	HPP	11	SB
			6.00	247	3114	HPP	5	SB, t 6.02
		55	3.00	280-300	2817	SE = 78	41	SB
			4.00	297-315	Mix 3046 to 3136		20	SB&S, t 4.06
		60	3.00	265-394	2854	SE = 15	34	SB&S
			4.00	290	3174	HPP	6	SS, t 4.03
				371	3097	2R(28)	5	SS
		65	3.00	300-305	3141	6R(73)	24	SS t 3.04
		70	2.00	291	2866	6R(70)	10	SS, t 2.01
			3.00	307	3146	HPP	4	SI, t 3.02
				341	3354	HPP	2	SS, t 3.05
				380	3265	4R(20)	10	SS

(a) These tests used nine special lots. See Firing Records P3127 and P40411.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 2. Armor Piercing Capped Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
105	T13	30	4.00	220	2115	LCP	1	E1; SB
(Mods E1, E2, and E3)			5.00	--	2187	6R(99)	14	E1, E2, E3; SI&B
			6.00	--	2664	LCP	2	E1, E2
		55	3.00	--	2612	2R(19)	3	E1; SI&B
105	T32E1	30	7.00	210	2537	SE = 18	27	SI&B
		45	5.00	221	2620	SE = 18	25	SI&S
			6.00	243	2890	6R(102)	9	SI&S
		55	4.00	225	2975	6R(155)	12	SB&S, t4.01
120	T14	20	8.00	209	2482	4R(58)	11	SI, t8.06
		30	8.00	208	2719	SE = 22	23	SI&B
		45	6.00	--	2892	SE = 43	46	SB&S
120	T14	0	8.00	238	2482	2R(41)	6	E3 w/cap; SL, t7.96
(Mods E1, E3)(a)		20	8.00	239	2669	2R(40)	8	E3 w/cap; SI&B, t7.96
		30	6.00	265	2439	2R(36)	5	E3 w/cap; SI, t6.02
			7.60	262	2823	4R(77)	6	E3 w/o cap; SI, t7.65
			8.00	210	2678	LCP	4	E1 w/cap; SL, t8.12
				210	3334	2R(137)	5	E1 w/o cap; SS, t8.12
		45	4.00	291	2427	4R(70)	5	E3 w/cap; SB, t4.04
			6.00	252-263	3180	6R(38)	11	E3 w/cap. SB
				225	2866	2R(41)	7	E1 w/cap; SL, t6.06
				225-252	3334	4R(132)	10	E1, E3 both w/o cap; SB&S, t6.05
		55	5.00	256	2999	6R(160)	6	E3 w/cap; SB
		60	3.00	269	2515	4R(63)	6	E3 w/cap; SB
			4.00	225-297	Mix 2806 to 3115		20	E3 w/cap; SB, t3.98
				233	2914	2R(26)	5	E3 w/o cap; SB
			5.00	266	3091	HPP	2	E3 w/cap; SB
		70	2.00	302	2200	4R(37)	6	E3 w/cap; SS

(a) These tests are those reported in Firing Records P464[illegible]1 and P413[illegible].

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 3. High-Velocity Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
75	T27	20	3.00	--	1888	2R(47)	6	
			6.00	--	2694	HPP	2	
		30	3.00	--	2303	2R(40)	3	
			5.00	--	2526	2R(46)	4	t 5.12
76	M93	0	6.00	213-225	2534	4R(94)	8	SI
			8.00	220 et al.	2975	4R(25)	13	SB
		30	4.00	220-229	2265	SE = 108	27	SB&S
			6.00	220-245	2343	SE = 19	16	SB
				320	Mix 2767 to 3357		13	
		40	4.00	320	3276	2R(52)	4	
				210	2968	SE = 86		
		45	4.00	250	3065	SE = 53	30	
				300	3765	SE = 298		
			6.00	220	--	--	2	SB, HPP(P) = 3403
		55	3.00	255	3394	4R(114)	6	SS
76	T4 (various mods)	0	3.25	235	1564	2R(129)	6	T4E17, SS, t 3.31
		20	3.25	235	1775	LCP	4	T4E17, SS, t 3.31
			4.00	220	2162	2R(81)	6	T4
			6.00	250	2724	2R(1)	13	T4, SB&S
				220	2719	LCP	5	T4E17, SS
			8.00	208	3167	2R(100)	6	T4, t 8.03
		30	3.00	231	1972	2R(10)	6	T4
			3.25	235	2072	2R(46)	3	T4E17, SS, t 3.31
			4.00	220-240	2595	SE = 80	49	T4, SS
				220-240	Mix 2279 to 2561		31	T4E17, SS
				220-225	Mix 2066 to 2525		125	T4E20, SB&S
			5.00	250	2825PP,	3040CP	3	T4, SS
			6.00	220	3039	2R(86)	5	T4, SS, t 5.37
		40	3.25	235	2440	4R([illegible])	6	T4E17, SS, t 3.31
		50	3.25	235	3100	2R(53)	6	T4E17, SS, t 3.34
		55	3.00	255	3342	HPP	5	T4, SS
				231	3300	HPP	2	T4E17, SS
			3.25	235	3355PP,	3545CP	4	T4E17, SS, t 3.31

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 3. High-Velocity Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal., mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
76	Special[a]	0	8.00	226 et al.	Mix 2623 to 3742		48	10 shot designs, SI&B
		30	4.00	285	2516	4R(115)	5	1 shot design, SB&S
			6.00	220-230	Mix 2638 to 3527		59	14 shot designs, SB
		45	4.00	235	Mix 3103 to 3294		13	3 shot designs, SI&S
			6.00	220	3775	HPP	7	3 shot designs, SB&S
		55	3.00	240-277	Mix 3154 to 3927		45	14 shot designs, SB&S
76	T29[b] (various models)	0	8.00	220	3612	2R(38)	6	T29E2
				220	2702	2R(28)	5	T29E5
		30	6.00	320	3793	HPP	3	T29
				320	3017	2R(28)	5	T29E2
				255	2671	2R(38)	5	T29E5
		45	4.00	240	3576	2R(15)	7	T29
		55	3.00	250	2856	2R(56)	5	T29E5
76	T66E3	30	4.00	289	2696	2R(36)	5	
			6.00	253	4056	6R(107)	10	
		60	2.00	--	--	--	0	176ARO
76	M331 (various models) (HVAP-DS)	0	7.00	246	2998	6R(144)	8	M331A2
		30	4.00	--	2669	2R(54)	7	M331A1
			6.00	248	3198	6R(73)	8	M331A2
			7.00	238-283	3332	SE = 41	47	M331
				248	3592	2R(3)	4	M331A1
				248	3499	6R(155)	6	M331E3[c]
				248	3433	6R(133)	6	Lot KNC-E-1[c]
				248	3572	6R(101)	8	Lot KNC-E-2[c]
				248	3611	6R(170)	6	Lot KNC-E-3[c]
			8.00	239	3815	6R(93)	8	M331A1
		45	4.00	300	3709	6R(59)	10	M331A2
		55	3.00	285-307	3588	SE = 43	61	M331A1
				285-307	3580	SE = 16	19	M331A2
		60	2.00	285	3110	6R(133)	11	M331A2
			3.00	283	3450	SE = 29	29	M331
				256	3386	6R(112)	10	M331A1
				281-295	3479	SE = 58	16	M331A2
			4.00	308	4323	HPP	3	M331A1

(a) The tests here summarized briefly are described in Firing Records P41546, P42035, and P43564. The tests involved 14 varieties of shot, generally related to the T4, but with several novel changes in geometry and materials. A brief description of these shots is not feasible, but they are described in the reference records.

(b) These tests are reported in Firing Records P46546 and P464[illegible].

(c) These tests are reported in Firing Record P53986. The lots vary metallurgically.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 3. High-Velocity Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal., mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	M304	0	7.60	258-304	2523	SE = 15	21	SI&B
		30	4.00	280	2178	SE = 37	21	SB
			5.00	275	2298	6R(59)	10	SB
				338	2397	4R(53)	10	SS, t 4.97
				220	2468	SE = 59		
			6.00	280	2559	SE = 41	165	SI&S, 392ARO
				300	2882	SE = 65		
			7.60	262	2936	4R(68)	10	SB, t 7.65
				297	3208	6R(166)	11	SI&B, t 7.47
			8.00	239	3140	2R(62)	9	SI&B, t 7.96
		45	4.00	280	Mix 3017 to 3208		30	SB, t 4.08. By probit, BL = 2938, SE = 201.
			5.00	275-320	3527	SE = 9	22	SS
			6.00	249	3723	HPP	10	SB, lone CP at 3700
				297	3548	HPP	8	SS, t 6.02
			7.60	275-297	3750	HPP	9	SB&S, t 7.54
		55	3.00	280	3011	4R(46)	5	SB, t 3.01
				200	3400	SE = 39		
			4.00	280	3607	SE = 18	61	SS
				360	3462	SE = 25		
		60	3.00	257-321	3285	SE = 46	34	SB&S
			4.00	290-358	3748	HPP	14	SS
				391	3556	5R(80)	13	SS, t 3.98
		65	3.00	257	3556	6R(64)	10	SS
				363	3640	2R(17)	10	SS, t 3.05
				391	3432	6R(71)	11	SS
		70	3.00	319-391	3846	HPP	7	SB&S
90	M304[(a)]	0	14.00	203	2822	2R(58)	3	
(w/20 lb core)		30	6.00	252	1689PP,	1951CP	4	SB
		45	6.00	252	3124	HPP	3	SS
90	M332	30	6.00	251-285	Mix 2599 to 3591		40	85ARO
			8.00	235	4100	HPP	3	
		60	3.00	302	3373	6R(129)	8	

(a) These tests with a 20-lb core are described in Firing Record P41354.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 3. High-Velocity Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	T30 (various models)	0	8.00	208-220	2481	6R(113)	12	T30E16, SI, t 8.0C
			10.00	220	2733PP,	2916CP	5	T30E16, SI&S
			12.00	220	3298	2R(53)	4	T30E16, SI&S, t 12.19
		20	6.00	245	2151PP,	2291CP	5	T30E16, SB&S, t 6.06
			8.00	220	2765	2R(54)	5	T30E16, SS
			10.00	205	3110	2R(67)	5	T30E16, SB&S
		30	4.00	220	1958	2R(41)	2	T30E16, SB&S, t 4.03
			6.00	244-245	2407	SE = 106	37	T30E16, SB&S, 110ARO
			8.00	220	2906	2R(74)	5	T30E16, SS
		45	4.00	220	2799	2R(108)	9	T30E16, SS, t 3.97
			5.00	210	3284	SE = 34	21	T30E16, SI&S
				260	3610	SE = 34		
				310	3693	SE = 39		
			6.00	244	3336	2R(60)	5	T30E15, SS, t 6.06
		55	3.38	235	3376	2R(93)	3	T30E8, t 3.31
90	T44	0	8.00	260	2605	SE small	23	SI&B. Parabola fitted with almost no overlap by PP's & CP's.
				330	2755	SE small		
				390	2665	SE small		
		10	8.00	339	2954	4R(103)	4	SI&S, t 8.06
				390	2665	4R(63)	5	SI&S, t 7.98
		20	8.00	339-390	3185	SE = 91	23	SI&S
		25	8.00	260	3026	2R(37)	10	SI&S, t 8.04
				339	3666	HTF	8	SI&S, t 8.0C
		35	8.00	260	3377	6R(156)	10	SI&S, t 8.04
				339	3699	HPP	4	SS, t 8.06
		40	8.00	260	3695	2R(8)	6	SI&B, t 8.04
		45	8.00	260	3721	HPP	2	SB&S, t 8.04
90	T53	0	14.00	--	3026PP,	3178CP	4	SI&B, t 14.25
		30	6.00	--	2212	2R(34)	5	SB, t 5.62
90	T65E4	55	4.00	228	3531	4R(69)	5	HVAP-DS, SB&S

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 3. High-Velocity Armor Piercing Projectiles Versus Rolled Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	T137[a] (various models) (HVAP-DS)	10	7.00	279	2561	6R(152)	9	E1 Mod 3[c]
				279	Mix 2595 to 2800		8	E9 Mod 3[d]
		30	4.00	277	4427	LCP	1	E9 Mod 3[d]
			6.00	262	3831PP,	4018CP	5	E1[c]
				262	Mix 3728 to 3948		13	E9 Mod 1, E9 Mod 2[d]
			7.00	242-254	3704PP,	3983CP	16	E1 Mod 3[c]
				242	4309PP,	4424CP	2	E9 Mod 3[d]
			8.00	235-249	Mix 3130 to 4201		26	E1 Mod 2[b]
				235	4637	HPP	3	E9 Mod 2[d]
		45	4.00	277	2904	2R(67)	8	E1 Mod 3[c]
		55	4.00	248-294	Mix 3608 to 3763		15	E0, E1 Mod 2, E2, E4[b]
				269-293	3707	12R(110)	30	E1, E1 Mod 3[c]
				248-300	3966	SE = 61	45	E0, E9 Mods 1,2,3[d]
				270	3900	2R(1)	6	E21[e]
			5.00	285-288	4317	HPP	8	E0, E2, E4[b]
				285	4260	HPP	1	E9[d]
		60	3.00	285	3624	2R(35)	5	E7, E8[c]
			4.00	248-294	4115	6R(93)	13	E0, E2, E4[b]
				248-308	Mix 3817 to 4159		15	E1 Mod 3, E7, E8[c]
				270-291	4627	HPP	6	E9, Mods 1 and 2[d]
105	T29E4	0	14.00	200	3562	2R(40)	4	SS
		30	6.00	242	2310	2R(54)	6	SS
			10.00	197	3326	2R(51)	7	SS
		45	4.00	225	2799	LCP	4	SS, BL(P) = 2830, 2R(62)
		60	4.00	225	3470PP,	3621CP	4	SS
155	T35	0	14.00	--	3385	HPP	3	SB, t 14.25
		30	6.00	--	2220PP,	2434CP	4	SB, t 5.88
			10.00	205	2862	4R(67)	8	SB&S, t 9.97
		45	6.00	--	2962	2R(26)	4	SS, t 5.97
155	T35E2 (w/30-lb core)	0	14.00	252	2042	2R(85)	3	
		30	6.00	203	2876	2R(77)	3	SB&S

(a) Many designs of HVAPDS-T, 90 mm, T137 were tested as part of Project TA1-1462. For a description of them, see pp 6, 7, and 8 of Report 28 on that project. The ones used above were 90/60-mm varieties.
(b) These models apparently had an 8.00-lb core with ogival nose.
(c) These models apparently had a 7.35 or 7.45-lb core with double conical nose.
(d) These models apparently had a 6.90-lb core with double conical nose.
(e) This model had a "very long" core of uncertain weight.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 4. Armor Piercing Projectiles Versus Cast Homogeneous Armor

Shot: Cal, mm	Shot: Model No.	Nom. Obl., deg	Plate: Nom. t, in.	Plate: BHN, kg/mm²	Ballistic Limit: BL(A), ft/sec	Ballistic Limit: Significance	Number of Rounds	Notes (Abbreviations explained on p 27)
37	M74	0	1.00	--	--	--	0	93ARO
				230	1225	SE = 22		
			1.50	280	1289	SE = 7	376	SI, 5ARO
				330	1120	SE = 26		
			1.75	252	1422	2R(45)	5	t 1.81
				230	1559	SE = 9		
			2.00	270	1672	SE = 6	520	SI
				310	1720	SE = 27		
				199-232	Mix 2049 to 2226		20	Probit analysis failed
			3.00	235-270	Mix 2004 to 2435		32	to converge.
				288-305	PP2252 to 2346		18	SI&S, t = 2.81 to 3.41
				150	1269	SE = 24		
		45	1.00	240	1525	SE = 26	60	SI&B
				320	1622	SE = 24		
		60	1.00	296-326	2409	SE = 17	156	SI&S
57	M70	0	2.00	220	1132	SE = 18		
				260	1187	SE = 9	76	SI
				300	1133	SE = 14		
			2.25	248-283	1249	SE = 64	20	
				190	1384	SE = 75		
			3.00	260	1652	SE = 14	309	SI
				330	1510	SE = 34		
				217-236	2076	6R(11.9)	12	SI
			4.00	242-277	2138	SE = 21	53	SI
				301	2244	2R(4)	4	SI
				323	2727	6R(84)	11	SS
		20	3.00	272	1859	6R(85)	10	SI&S, t 3.10
		30	4.00	323	2075	HPP	5	SS, t 4.16
				220	2170	SE = 28		
		35	3.00	270	2545	SE = 13	37	SI&S
				320	2425	SE = 13		
		40	2.00	251	1890	2R(25)	9	SS, t 2.06
				230	2825	SE = 20		
			3.00	260	2700	SE = 30	36	SI&S
				310	2522	SE = 22		
		50	2.00	284-301	2414	SE = 35	21	SI&S
		55	2.00	253-287	2504	SE = 29	166	SI&S
				200	2820	SE = 53		
		60	2.00	300	2762	SE = 10	147	SI&S
				400	2845	SE = 120		
		65	2.00	255	2955	2R(109)	6	SS, t 2.04

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 4. Armor Piercing Projectiles Versus Cast Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Signifi- cance	of Rounds	(Abbreviations explained on p 27)
75	M72	0	3.00	190	1156	SE = 65	1015	SI
				250	1248	SE = 7		
				310	1194	SE = 35		
			3.25	248	1263	HPP	2	
			4.00	160	1466	SE = 85	190	SI
				230	1602	SE = 19		
				300	1718	SE = 46		
			6.00	228	2058	HPP	2	SI
		20	4.00	193	1852	2R(67)	4	SB
76	M79	30	3.00	239	1959	2R(92)	8	SS, t 2.85
76	T128E6 (M339)	20	4.00	251	2118	6R(122)	11	SB&S, t 4.02
		30	2.00	255	1210	2R(15)	8	SI&B, t 2.04
			4.00	251	2610	6R(81)	8	SS, t 4.02
		45	2.00	255	1768	2R(21)	7	SI, t 2.04
			4.00	251	2824	2R(43)	7	SB&S, t 4.02
		55	4.00	251	3212	6R(100)	9	SS, t 4.02
90	M77	0	3.00	190	1084	SE = 66	61	
				240	1099	SE = 20		
				290	1135	SE = 70		
			4.00	190	1433	SE = 63	177	SI, 346ARO
				240	1452	SE = 21		
				290	1356	SE = 40		
			5.00	218-259	1699	SE = 44	23	SI
			6.00	183-232	2007	SE = 25	49	SI
			8.00	206	3124	HPP	1	SS
		20	8.00	206	3112	HPP	1	SS
		30	4.00	280	2091	4R(72)	7	SI, t 3.84
		40	3.00	237	1983	LCP	2	SS, t 2.95
		45	3.00	237-269	1845	2R(46)	7	SS, t 2.84
90	T33	0	4.00	--	--	--	0	26ARO
			6.00	241-255	2144	LCP	8	BL(P) = 2162, 2R(37)
			8.00	206	3167	HPP	1	SS
			10.00	197	3150	HPP	2	SS
		30	8.00	206	3139	HPP	1	SS
		45	3.00	207-256	2893	SE = 32	14	SS
		55	4.00	252-272	2803	SE = 41	40	SB&S
		60	3.00	286-316	2502	SE = 12	70	SB&S
			4.00	270-274	3113	SE = 131	21	SB

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 4. Armor Piercing Projectiles Versus Cast Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Signifi-cance	of Rounds	(Abbreviations explained on p 27)
90	T33E7	0	4.00	232	1701	4R(80)	6	SI, t 3.97
(Not part of			5.00	235	1610PP,	1731CP	9	SI, t 5.19, BL(P) = 1766
Project AX23)			6.00	248	2090	6R(131)	8	SI, t 6.01
		20	6.00	248	2136	LCP	7	SI&S, t 5.99, BL(P) = 2196
		30	4.00	232	1866	4R(65)	8	SI&B, t 3.97
		45	5.00	235	2761	6R(115)	6	SS, t 5.19
		55	4.00	219	2671	6R(149)	7	t 3.99
		60	3.00	233	2746	2R(62)	8	t 3.02
90	T54E1	0	7.60	247	2459	6R(117)	10	SI&B, t 7.55
		30	5.00	238-258	2553	SE = 15	20	SB&S
			6.00	254-260	2876	SE = 31	20	SS
			7.60	245-260	3289	HPP	11	SB&S, t 7.53
		45	4.00	243-282	2487	SE = 52	22	SB&S
			5.00	238-273	2732	SE = 35	20	SB
			6.00	246-267	3232	SE = 82	20	SB
		55	3.00	258-266	2410	SE = 34	20	SB&S
				326	2232	SE = 24	10	
			4.00	220	2850	SE = 37	15	SB&S
				288	2618	6R(41)	11	
		60	2.00	224	2263	4R(82)	7	SB, t 2.08
			3.00	230-300	2675	SE = 39	30	SB&S
				220	2990	SE = 34		
			4.00	260	3084	SE = 38	43	SB&S
				300	2997	SE = 28		
			5.00	239	3200	HPP	4	SB, t 5.16
		65	3.00	221-300	2871	SE = 30	20	SB&S
			4.00	238	3399	HPP	3	SS, t 4.20
				238	3144	2R(1)	10	SS, t 4.04, lone CP
		70	2.00	222	2928	4R(49)	6	SB, t 1.98
			3.00	223	3228	4R(31)	10	SB, t 3.02
				258	3109	6R(80)	9	SB&S, t 3.06

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 4. Armor Piercing Projectiles Versus Cast Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm²	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
120	T116	30	6.00	248	2091	6R(95)	9	E5, SB, t 6.01
(Mods E4, E5)			7.60	252	2779	4R(34)	8	E4, SB, t 7.62
		45	4.00	275	2010	4R(55)	5	E4 w/o WS, SS, t 4.16
			5.00	280	2239	6R(148)	7	E4 w/o WS, SS, t 5.16
			6.00	238-244	2923	6R(132)	10	E4, SS, t 5.99
				249	3130	6R(89)	8	E5, SS, t 6.27
			7.60	252	3135	HPP	3	E4, SB, t 7.62
		55	5.00	233-274	2693	SE = 40	64	E4, SB&S
			6.00	246	3336	HPP	7	E5, SS, t 6.26
		60	2.00	243-244	1593	LCP	9	E5, SB, t 2.06
			3.00	275	2336	6R(96)	8	E5, SS, t 3.13
				325	2322	6R(94)	9	E4 w/o WS, SS, t 3.16
			4.00	249	2600	6R(103)	7	E5, SS, t 4.18
				280	2297	6R(123)	9	E5, SB, t 3.90
			5.00	239	2854	2R(32)	5	E4, SS, t 4.96
				284	2993	6R(114)	7	E4 w/o WS, SS, t 5.21
		65	4.00	246	3277	HPP	5	E5, SS, t 4.17
		70	2.00	244-251	2008	2R(41)	7	E5, SB, t 2.07
			3.00	323	2606	2R(50)	7	E4 w/o WS, SS, t 3.12
				252-274	2886	6R(91)	15	E5, SS, t 3.12
			4.00	246	3314	HPP	5	E5, SS, t 4.17
				285	3138	4R(78)	7	E5, SS, t 4.18
		75	2.00	253-257	2632	4R(60)	8	E5, SB, t 1.99
155	M112	0	6.00	192-230	1509	2R(18)	21	SI, only one PP
			6.00	206	2462	LCP	4	SI&S
			10.00	197	2682	HPP	3	SB
		30	4.00	212-280	Mix 1382 to 1468		16	SI, only 2 PP, 234ARO
			5.00	259	1722	4R(97)	7	SI, t 4.90
			6.00	183-255	1771	SE = 129	48	SI, mostly acc. tests
		45	4.00	236-241	1872	2R(76)	5	SI&B, t 3.94
			6.00	185-226	2590	6R(141)	8	SI&S, t 6.04
6-in Mk XXVII		15	6.00	185-195	1548	6R(162)	8	t 5.81, 38ARO

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 5. Armor Piercing Capped Projectiles Versus Cast Homogeneous Armor

Shot: Cal, mm	Shot: Model No.	Nom. Obl., deg	Plate: Nom. t, in.	Plate: BHN, kg/mm^2	Ballistic Limit: BL(A), ft/sec	Ballistic Limit: Significance	Number of Rounds	Notes (Abbreviations explained on p 27)
37	M51	0	1.00	260	1045	SE = 14	53	SI
				310	995	SE = 7		
				360	948	SE = 11		
			1.50	248-311	1584	SE = 56	111	SI
			2.00	242-302	1817	SE = 32	138	SI
			2.25	252-283	2032	SE = 19	70	SI
			3.00	269	2364	2R(21)	5	SI, t 2.87
		20	1.00	262-332	1167	4R(62)	17	SI, t 1.08
				364	1042	2R(33)	3	t 1.01
		30	1.00	260	1368	SE = 55	29	SI
				310	1369	SE = 28		
				360	1205	SE = 56		
		35	2.00	200	2273	SE = 57	297	SI&S
				250	2436	SE = 12		
				300	2624	SE = 31		
		40	1.00	262	1903	LCP	1	
		45	1.00	260	1875	SE = 41	48	SI&B
				310	1968	SE = 24		
				360	1868	SE = 44		
		55	1.00	262-364	2326	SE = 31	37	SI&B
57	M86	0	3.00	269-272	1849	6R(108)	13	SI, t 2.99
			4.00	323	2278	6R(57)	11	SI&S, t 4.16
		30	1.50	235-330	1224	SE = 50	17	
			4.00	323	2921	HPP	4	SS, t 4.16
		35	1.50	235-269	1501	2R(6)	6	t 1.56
				302	1403	LCP	3	t 1.55
				330	1163	LCP	3	t 1.41
			2.00	251	1783	6R(79)	6	SI&B, t 2.06
			2.50	254	2073	6R(112)	12	SI, t 2.57
			3.00	220	2352	SE = 41	76	SI&S
				270	2491	SE = 26		
				320	2563	SE = 43		
		45	1.50	230	1531	SE = 70	47	
				280	1727	SE = 35		
				330	1195	SE = 65		
			3.00	272	[illegible]	2R(96)	6	SI, t 3.10
		50	2.00	264-303	2380	SE = 30	30	SI&B
		55	1.50	235-302	2076	LCP	11	t 1.92
				330	1690	2R(42)	4	
			2.00	264-303	2726	6R(70)	13	SI&B, t 2.04
		60	2.00	254-301	2712	HPP	9	SI&B, t 1.99

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 5. Armor Piercing Capped Projectiles Versus Cast Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes	
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)	
75	M61	0	3.00	269	1418	2R(37)	7	SI, t 2.82	
			4.00	268	1940	2R(48)	5	SI	
		25	1.25	262	972	HPP	1	SI, t 1.19	
			1.50	284	962	HPP	2	SI	
		45	1.00	340	1991	4R(127)	6	SS, t 1.02	
76	M62	0	2.00	241-291	1092	6R(87)	16	t 2.08	
				314	912	LCP	4	t 2.08	
			4.00	280	2014	2R(44)	3	t 3.87	
		20	3.75	217	1871PP,	2033CP	8	SI	
			4.00	188-207	Mix 2047 to 2628		20	SI	
		30	2.00	243-307	1243	6R(84)	17		
			3.00	269	1720	4R(100)	5	SI, t 2.82	
			4.00	204-245	2286	4R(82)	10	SI, t 3.94	
				273-321	2599	2R(8)	7	SI&S, t 3.94	
				220	2379	SE = 24			
		35	4.00	250	2339	SE = 35	46	SI&S	
				280	2734	SE = 25			
				210	1790	SE = 57			
		45	2.00	260	1672	SE = 44	132	SI	
				310	1590	SE = 59			
			2.25	259-311	1896	6R(53)	13	t 2.30	
			2.50	259-266	2291	SE = 24	28		
				240-243	2129	6R(126)	12	t 2.10	Probit
		55	2.00	282-285	2150	4R(92)	6	t 1.94	analysis
				307	2211	6R(39)	11	t 2.05	diverged
90	M82	0	3.00	237-269	2043PP,	2212CP	6	t 2.95	
			4.00	217-280	1687	SE = 13	46	SI	
			5.00	218	2156	LCP	4	SI, t 5.12	
			6.00	195-232	2341	6R(145)	28	SI	
			8.00	206	3186	HPP	2	SB	
			10.00	197	3167	HPP	2	SI	
		20	8.00	206	3170	LCP	2	SI&B	
		30	3.00	235-303	1609	SE = 22	47		
				200	2115	SE = 83		SI for BHN ≤ 280	
			4.00	260	2087	SE = 36	110	SI&S for BHN ≥ 321	
				320	2361	SE = 98			
			6.00	226-228	2728	HPP	3		

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 5. Armor Piercing Capped Projectiles Versus Cast Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	M82	35	2.00	253	2346	2R(49)	2	SI, t 2.03
		40	4.00	229-301	2591	2R(4)	5	SI, t 3.97
				190	2109	SE = 101		
		45	3.00	260	2263	SE = 20	212	SI&B
				330	2139	SE = 80		
			3.25	248	2189	2R(50)	3	SI&S
			4.00	199-280	Mix 2583 to 3220		82	SI&S[a]
		55	3.00	264	2593	HPP	1	t 3.02
				230	2286	SE = 17		
90	T39	30	5.00	250	2216	SE = 14	61	SI
				270	2328	SE = 15		
		55	4.00	245	3129	HPP	4	SB, t 4.04
		60	3.00	253	2744	6R(104)	10	SB, t 3.02
90	T50E1	0	7.60	247-269	2652	SE = 24	24	SI
		30	5.00	238-258	2280	SE = 13	33	SI
			6.00	254-260	2623	SE = 63	[illegible]	SI
			7.60	245-260	2943	SE = 21	[illegible]	SI
		45	4.00	238	2479	6R(140)	[illegible]	SI&B, t [illegible]
				281	2652	6R(171)	10	SB, t 3.94
			5.00	238-241	2928	SE = 19	31	SI&B
			6.00	254-267	3259	HPP	13	SI&S, t [illegible]
		55	3.00	249-280	2863	SE = 89	21	SS
			4.00	245	3136	4R(147)	6	SB, t 4.04
				288	2727	2R(2)	7	SS, t 3.95
		60	2.00	225	2158	4R(52)	11	SI, t 2.01
			3.00	279-303	2749	SE = 21	21	[illegible]
			4.00	220-304	3213CP, 3447PP		[illegible]	[illegible], 21 PP's ≤ 3188
		65	3.00	262	3152	6R(60)	7	SI&S, t 3.07
		70	2.00	238	Mix 279[illegible] to 2988		11	SS, t 2.07
			3.00	249	3350	HPP	[illegible]	[illegible]
120	T14E3	30	7.60	246-269	2641	SE = 11	[illegible]	[illegible]
		45	6.00	248-267	2945	SE = 55	[illegible]	SB
			7.60	269	3103	HPP	[illegible]	SB, t 7.[illegible]
		60	3.00	236-255	2[illegible]70	6R(123)	12	SI&S
			4.00	246-260	2763	6R(132)	12	[illegible]
			5.00	244-260	3046	6R(74)	9	SI&S, t 5.11
		70	3.00	251	3118	6R(80)	7	[illegible], t 3.13
			4.00	236	3318	HPP	5	SS, t 4.23

(a) Penetration in this group seems little related to either velocity or plate hardness. The data were drawn from [illegible], AD[illegible], AD866, and Firing Record AR18866. Over 20 plates were used in these tests.

TABLE 3. SUMMARY OF BALLISTIC LIMITS

Part 6. High-Velocity Armor Piercing Projectiles Versus Cast Homogeneous Armor

Shot		Nom.	Plate		Ballistic Limit		Number	Notes
Cal, mm	Model No.	Obl., deg	Nom. t, in.	BHN, kg/mm^2	BL(A), ft/sec	Significance	of Rounds	(Abbreviations explained on p 27)
90	M304	0	7.60	245-269	2414	SE = 13	32	SI
		30	5.00	236-273	2220	SE = 15	22	SB
			6.00	254-260	2482	SE = 24	21	SB
			7.60	245	2782	6R(95)	10	SI
		45	4.00	243	2728	6R(138)	10	SS, t 3.94
				282	2862	2R(3)	10	SS, t 3.85
			5.00	236-273	3128	SE = 57	22	SB at 236, SS at 273
			6.00	246-267	3673	SE = 41	21	SS
			7.60	247	3744	HPP	4	SB
		55	3.00	243-280	2759	SE = 23	21	SB at 243, SS at 280
			4.00	231-280	3374	SE = 13	23	SB
		60	3.00	243-272	2991	SE = 11	20	SB at 243, SS at 272
			4.00	258-266	3795	HPP	14	SB&S, t 4.05
				301	3686	6R(101)	10	SS, t 3.93
			5.00	239	3750	HPP	4	SB, t 5.16
		70	3.00	245-280	3853	HPP	8	SB at 245 w/t 3.08; SS at 280 w/t 3.11
90	T30E15	20	10.00	197	2893PP,	3065CP	3	SS
90	T44	0	8.00	223	2513	4R(36)	10	SI, t 8.02
		25	8.00	223	2816	6R(101)	11	SI&S, t 8.02
		35	8.00	223	3248	6R(39)	10	SI&S, t 8.02
		40	8.00	223	3445	6R(72)	10	SI&B, t 8.02
		45	8.00	223	3660	2R(25)	6	SI&S, t 8.02
		50	8.00	223	3672	HPP	3	SS, t 8.02
155	T35	30	4.00	207	1467	HPP	1	

APPENDIX

BIBLIOGRAPHY

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Following is a list of the principal references that were edited to get the penetration data that were analyzed.

Projects TB4-150M and TB4-10 (Approximately 4,600 rounds)

Ar 16981	Ar 17094	Ar 17186	Ar 18065	Ar 20802
16983	17131	17390	18065sup	20949
16984	17146	17845	18084	21080
16985	17154	18060	18084sup	21203
16988	17158	18223	19675	21344
16994	17163	18494	19843	
17050	17221	19106	20701	

Project TT1-5 (Approximately 1,400 rounds)

Ar 17784	Ar 17826	Ar 18490	Ar 18752	Ar 19447
17791	17838	18513	19076	19476
17792	17910	18513sup	19182	20526
17794	18073	18553	19183	
17796	18073sup	18553sup	19187	
17798	18107	18658	19276	
17804	18489	18703	19366	

Project AX23 (Approximately 500 rounds)

Ar 19945k	Ar 20318	Ar 20730	Ar 20895

Project TB3-1224 (Approximately 200 rounds)

Ar 18504	Ar 21421

O. P. 2864, Effect of Hardness (Approximately 3,400 rounds)

AD 558	AD 838	AD 1043	A-12581	A-12614
AD 586	AD 992	AD 1064	12582	Ar 16231
AD 679	AD 1007	AD 1080	12580	
AD 686	AD 1041		12585	
AD 834	AD 1042		12606	

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Miscellaneous Test Programs on R. H. Armor (Approximately 1,400 rounds)

AD 210	AD 542	AD 689	AD 844	AD 1084
AD 369	AD 574	AD 830	AD 1014	
AD 509	AD 652	AD 839	AD 1033	Ar 13801

Miscellaneous Test Programs on C. H. Armor (Approximately 2,400 rounds)

AD 517	AD 590	AD 678	AD 836	AD 1074
AD 560	AD 630	AD 685	AD 990	AD 1076
AD 571	AD 658	AD 694	AD 999	Ar 15244
AD 587	AD 663	AD 697	AD 1012	Ar 15256

Acceptance Tests of Armor Plate (Approximately 2,400 rounds)

Records From These Library Books BC114I

127C	127G	127M2	127Q	BC163B
127C2	127G1	127M3	127S	BC163C
127D	127K10-5	127M4	BC114A	BC174
127D1	127L	127M7	BC114C	BG4
127D2	127M1	127M10-1	BC114E	C74A

Shot Design Projects (Approximately 2,700 rounds)

O.P. 5870	Project TA1-1251	Some single reports:	
5757	TA1-1254	ADP194	P35543
5758	TA1-1301	ADP197	P39979
6132	TA1-1302	P25184	P41354
5591	TA1-1460	P34137	P56080
	TA1-1503	P34144	

Acceptance Tests of Shot (Approximately 1,200 rounds)

Records From These Library Books

A128	BG21	BG28	DA88	DA128
BC163D	BG22	DA21	DA99	EB41
BG16	BG26	DA74	DA104	

Other Firing Records

P53966 to P60803, 21 records on the HVAPDS, 76 mm, M331
P52520 to P54821, 7 records on the AP, 90 mm, T33

A-3 and A-4

Following is a list of the principal references that were edited, but that were not used in the analysis.

Acceptance Tests of Armor Plate (Approximately 800 rounds)

Records From These Library Books

				127M7
127C	127D1	127G1	127M4	127Q
127C2	127D2	127M1	127M5	127S
127D	127G	127M2	127M6	A128A

Acceptance Tests of Shot (Approximately 11,400 rounds)

Records From These Library Books

A103	AN2	BC163	C74A	DA74
A128	AN4	BC163A	C74B	DA88
A128A	AN7	BC163B	C95	DA99
A136	AN12	BC163C	C96	DA128
AN	BC114B	BC163D	DA13	
AN1	BC114E	BC174	DA21	

Other Firing Records

P52366 to P55575, 15 records on the AP, 90mm, T33

Following is a list of references which were not edited, but apparently contained material that could have been used.

Shot Design Projects (Approximately 700 rounds)

Project TA1-1475, Report 1 and 6 other firing records
TA1-1602, Reports 1, 2, 8 and 5 other firing records
TA1-5002, Report 3 and F. R. P-60401
TA1-1302, Report 13

Acceptance Tests of Shot (Approximately 800 rounds)

Records From These Library Books

BC-114-B, C, D, and E, 30 records on the AP, 75mm, M72 and APC, 75mm, M61, BC163 and BC163A, 27 records on the AP, 75mm, M72 and APC, 75mm, M61

Other Firing Records

P-48161 to P-62446, 45 records on the AP, 120mm, T116

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