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REPORT NO. WAL 710/795

Historical Review of the Correlation of

Ballistic and Metallurgical Characteristics of Domestic

Armor at Watertown Arsenal

BY

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WATERTOWN ARSENAL
WATERTOWN, MASS.

7 December 1945

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Watertown Arsenal Laboratory
Report No. WAL 710/795

7 December 1945

Historical Review of the Correlation of Ballistic and Metallurgical Characteristics of Domestic Armor at Watertown Arsenal

OBJECT

To summarize the work conducted at Watertown Arsenal covering the correlation of metallurgical and ballistic properties of armor.

SUMMARY

The correlation of metallurgical characteristics with ballistic properties has been a continuous, ever improving process. As the factors were learned that made for good ballistic performance, specification requirements were raised and better armor was demanded of industry. By the end of 1943, the correlation of microstructure, static and dynamic physical properties with the ballistic properties was so well established that it was possible to utilize non-ballistic tests for inclusion into the specifications to eliminate unsuitable armor prior to ballistic testing. Later, for armor 6" and thicker, non-ballistic tests (hardness and V-notch Charpy) were substituted for ballistics. Today it is believed that the metallurgical characteristics required for optimum ballistic performance are known for homogeneous rolled and cast plate; the problem is one of achieving these characteristics, especially as the armor thickness increases. Furthermore, by means of hardness and fracture tests alone it is possible to predict ballistic results fairly successfully.

It is difficult to predict the future of correlations between ballistics and metallurgical properties of armor. Certainly this will continue to be one of the chief objects in all future development work. One field that obviously offers much opportunity for study is carburized armor. Another is armor made of metals and alloys other than steel, such as aluminum and magnesium alloys.

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INTRODUCTION

The history of the correlation of ballistic and metallurgical characteristics of domestic armor is recorded in the sum of almost all the reports written by the Armor Section of Watertown Arsenal, for this correlation has been one, if not the primary, aim in almost every investigation of armor conducted at this arsenal. In order to transfer to the reader an understanding of the procedures employed whereby samples of armor were received at Watertown Arsenal and metallurgically examined and the information gained therefrom was correlated with ballistic test data and then disseminated in reports, a brief background section is therefore desirable.

The various categories of armor with which the Watertown Arsenal has been primarily concerned are as follows: (1) rolled homogeneous; (2) cast homogeneous; (3) rolled face hardened; (4) aircraft; (5) helmet; (6) body; and (7) foreign. This report pertains only to the first three types. It is pointed out at this time that cast armor was employed in the production of tank turrets, tank hulls, and gun shields. In tanks, rolled homogeneous armor was used mainly for the side, top, and bottom plates. (Some hulls were composed entirely of rolled armor.) The protection of armored vehicles other than tanks was afforded in the main by rolled armor, homogeneous and/or face hardened.

Although experimental armor projects were initiated and carried out completely at Watertown, the overwhelming majority of the armor samples examined were supplied by Aberdeen Proving Ground. Generally, samples of armor were received from the latter facility with a request for metallurgical examination in order to supplement the ballistic tests already conducted upon the armor. The samples may have represented plates fired at Aberdeen for qualification or acceptance, in accordance with the pertaining specification. They may have represented plates tested as part of a development program or as part of a project initiated to develop or improve a specification; or the samples may have been part of a special project, such as the program conducted in 1942 to decrease the alloy content of armor.

Ballistic testing, whether conducted at Watertown Arsenal, at Aberdeen Proving Ground, or at some other firing range, and whether performed on acceptance or experimental armor, generally had as its object the evaluation of the following three armor characteristics; resistance to penetration, resistance to back spalling, and resistance to shock. Since these characteristics and the procedures employed in ballistic testing are adequately (although briefly) contained in the writeup[1] on "Development of Non-Ballistic Tests of Armor at Watertown Arsenal", there is no need for elaboration in this report. For a more complete picture of ballistic testing the reader is referred to the report[2] by Zornig, et al, written in August 1944.

1. A. Hurlich, "Development of Non-Ballistic Tests of Armor at Watertown Arsenal", Historical Writeup for J. E. Pfeiffer.

2. H. H. Zornig, N. A. Matthews, and C. Zener, "Armor Plate Ballistic Testing", 2 August 1944, Report Number WAL 710/685.

Upon completion of the ballistic testing, samples, usually ranging from 6" x 6" x plate thickness to 16" x 16" x plate thickness (depending on the armor gauge), were flame cut from the armor and transported to Watertown Arsenal. Here the material was examined visually and then various metallurgical tests were conducted. Up to 1939 these tests consisted of only chemical analysis, hardness surveys, macroscopic examination, and microscopic examination. Tensile and Jominy hardenability tests were added by the early part of 1942, and since the beginning of 1943 fracture tests for steel soundness and fiber and V-notch Charpy tests were also employed. At various times other tests, such as tensile impact and tensile tests across the plate thickness, were investigated but found to be of no value and were not used further.

Prior to 1940 all metallurgical investigations were written up in experimental reports, unless the examination was of an abbreviated nature, in which case the pertinent information gained was forwarded to the interested ordnance agency or manufacturer by letter. The use of letters has continued until today for the above purpose and also to furnish quickly a condensed version of the immediate results of an investigation still in progress. Such letters are known as "letter reports" but are filed as regular correspondence and are not designated by report identification. With the establishment of the Subcommittee for Cast Armor in September, 1940, and the Subcommittee for Rolled Armor in October, 1940 additional methods were sought for distributing to the members the results of metallurgical investigations or other data which were of particular interest to them. This was accomplished by means of the Cast Armor Subcommittee Reports and the Rolled Armor Subcommittee Reports, which are still in use but were issued mainly from December, 1940 to March, 1943. In October, 1943, another classification was established to provide means for recording metallurgical investigations which were not qualified for writeup in experimental report form. This type of writeup, known as the memorandum report, was used mainly to record, in a condensed fashion, either the routine examination of armor plate samples received from Aberdeen Proving Ground or individual phases of programs being conducted at Watertown Arsenal. The experimental report was reserved for projects requiring either experimental laboratory work or extensive correlation of data. A complete list of the reports related to the subject matter of this writeup are contained in Appendix A, arranged chronologically.

From now on, by means of these reports, the reader will trace the paths by which the Watertown Arsenal arrived at its present understanding of the correlation between the metallurgical and ballistic characteristics of domestic armor.

DISCUSSION

A. What Was Known Prior to 1940

Prior to 1940 armor manufactured for the United States Ordnance Department consisted almost entirely of rolled plate, and the armor was of relatively light gauge. The maximum thickness provided for by the specifications (except for one minor specification in 1938) was 1". Both homogeneous and face hardened armor were acceptable by the Ordnance Department but ballistic requirements were so high that production consisted mainly of the latter type of armor (whose hard face was due to carburizing).

From a series of investigations made during the period 1927-1936 it had been concluded that good quality armor should be free from pronounced segregation of non-metallic inclusions and possess a uniform microstructure. In 1938 the first metallurgical investigations designed for the purpose of correlating metallurgical characteristics with ballistic properties were conducted on both rolled homogeneous and rolled face hardened plates.

Samples of rolled homogeneous plates accumulated over the period of years from 1922 to 1938 were examined metallurgically and the data were correlated with the results of ballistic tests previously performed. Forty seven plates were included, ranging in thickness from 1/8" to 1" but consisting mainly of the 3/8" and 1/2" gauges. Metallurgical tests consisted of macro etching in Oberhoffer's reagent, Brinell hardness, chemical analysis, and microscopic examination. Results of the ballistic-metallurgical correlation were based on resistance to penetration tests only, shock test data not being available. Plates 1/2" and lighter were tested at normal with caliber .30 AP ammunition; heavier plates were tested with caliber .50 AP at normal obliquity.

The report[1] summarizing this project was entitled "Correlation of Microstructure and Ballistic Properties of Armor Plate, Part I, Homogeneous Plate". Conclusions were as follows:

"1. Laminations of any considerable extent are a primary cause of spalling in plate of passable ballistic limit.

"2. Carbides (or any other segregates which may be revealed by a Murakami etch) in definite chains in grain boundaries produce spalling. Segregations of these constituents into bands or patches contribute to spalling, but do not of themselves produce it under tests made with caliber .30 armor-piercing single shot.

"3. Martensitic structure invariably caused spalling, while a fairly uniform troostito-sorbitic structure was found in the majority of high ballistic non-spalling plate. (Author's note: a troostito-sorbitic structure is softer than a martensitic structure.)

"4. Eliminating all plate with laminations, bad carbide conditions and non-uniform nital structure, Brinell hardnesses from 418 to as high as 444 were found to produce the highest ballistic plate which did not spall under the caliber .30 AP tests to which they were subjected.

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1. Appendix A, Report No. 1

"5. Macro segregations in the form of banding (in the absence of elongated non-metallic inclusions) were found in both high and low ballistic plate."

The investigation of face hardened armor was conducted upon samples of carburized plates made at Watertown Arsenal and rolled by Henry Disston and Sons, Inc., which had accumulated over the period of years from 1922 to 1938, and upon some "recent" Diebold and Disston 1" - 1½" carburized plates. Thickness ranged from 1/8" to 1½" but were mainly 1/4" and 1/2". Again the ballistic firing consisted of resistance to penetration tests, at normal obliquity, except for the addition of caliber .50 AP angle shots against three of the 1/2" plates. Ballistics were as follows: 1/8" to 3/8" plates, caliber .30 AP; 1/2" plates, caliber .30 AP and .50 AP; 5/8" and 1", caliber .50 AP; and 1-1/4" and 1-1/2", 37 mm. AP. The same metallurgical tests were used as in the case of the homogeneous plates.

The investigation of the 31 carburized plates examined was entitled "Correlation of Microstructure and Ballistic Properties of Armor Plate, Part II, Face Hardened Plate".[1] It was concluded that

"1. Laminations (elongated non-metallic inclusions) present to an extent which would cause spalling in homogeneous plate, do not produce this result in carburized plate when tested with caliber .30 AP because of the protection afforded by the face.

"2. Carbides (or any other constituents which may be revealed by a Murakami etch) segregated to any extent in the grain boundaries of the case are detrimental to the extent that 75% of the brittle plate had this bad carbide condition, whereas only 25% of the acceptable plate showed a similar condition, and each plate of this 25% showed slight petalling.

"3. The microstructures of most carburized cases ranged from a troostite to a troostito-sorbite.

"4. Martensitic structures in the core invariably caused spalling, while a uniformly distributed ferrite in sorbite was found in high ballistic non-spalling plate.

"5. Plate which passed specification had an average face hardness of 542 Brinell and an average core hardness of 372 Brinell, while plate which, although ballistically ductile, failed to meet ballistic limit requirements had an average face hardness of only 465 Brinell, and an average core hardness of 363.

"6. No relation could be found between the normal banding revealed by an Oberhoffer's etch and the ballistic properties."

1. Appendix A, Report No. 2.

The effects of high hardness and grain boundary carbides on the ballistic ductility of 1" homogeneous rolled plate were further investigated in 1939[1], when it was concluded:

> "1. Plates which were originally brittle can be made ballistically ductile by proper heat treatment to obtain structures and hardness as specified in Specification AXS-54-L (Author's note: i.e., by tempering the quenched plate to lower hardness).
>
> "2. High temperature normalizing will greatly increase the ductility of the plate by inducing a solution of the carbides, providing the carbides in the original plate are not too large or too greatly segregated."

B. Rolled and Cast Armor from 1940 to the Development of Low Alloy Armor (Early in 1942)

In a report[2] written in May 1940, it was shown that face hardened plate of all thicknesses currently produced (1/4" to 1") was ballistically superior to homogeneous plate of corresponding thickness. The report was a survey of the ballistic limits of all the light armor plates, face hardened and homogeneous, whose ballistic properties were given in the Aberdeen reports of ballistic tests made in the period 1938 to March 18,1940. No attempt was made to isolate the effects of depth of case, Brinell hardness, chemical composition, heat treatment, or manufacturer's process on the ballistic properties.

Realizing, however, that the availability and capacity for manufacture of face hardened armor would be inadequate in time of emergency, Watertown Arsenal proposed that the emphasis be shifted to the development of homogeneous armor. Because the specified limits for rolled homogeneous armor were so excessive during this period, the manufacturers were being forced to manufacture face hardened (i.e. carburized) armor to meet the requirements.

In two subcommittee reports[3] issued in January and February, 1941, it was proposed that in order to secure satisfactory plate (i.e. readily machinable) a Brinell range of 285 to 335 be specified and the ballistic limit requirements for 1/2", 3/4", and 1" plate be lowered to values capable of being achieved by plate of this hardness range. Subsequently, in 1941 two specifications were issued for homogeneous plate only, covering the thickness range 1/4" to 2", in which the ballistic limits were lowered considerably. Thereafter the emphasis in the development of rolled plate was placed on the homogeneous type.

1. Appendix A, Report No. 3.
2. Appendix A, Reports Nos. 6 and 101.
3. Appendix A, Reports Nos. 31 and 33.

During the period from 1940 until the development of low alloy rolled plate, early in 1942, little knowledge was added to that already known concerning the correlation between metallurgical properties and ballistics of rolled homogeneous plate except for the concept that armor made from compositions low in alloy content was as satisfactory as similar armor fabricated from the high alloy analyses then in use. This concept will be dealt with further in Section C.

Freedom from segregations of non-metallic inclusions and grain boundary carbides, and the presence of a uniform sorbitic microstructure were emphasized as the characteristics of good rolled homogeneous armor in the reports[1] written covering the investigations conducted during this period and by the reissue, at this time, as subcommittee reports[2], of some experimental reports written prior to 1940. In addition, it was concluded from an investigation[3] of two 1-1/2" plates, one of which passed and one of which failed by back spalling under the shock test impact of the 75 mm. APT12 projectile at 25° obliquity, that 311 Brinell was excessive for this gauge plate.

During this period tensile, tensile impact, and Vickers Brinell hardness tests were added to the metallurgical tests used for examining rolled homogeneous armor and several reports[4] were issued that described and evaluated the various metallographic means of determining the presence of grain boundary carbides.

With the exception of two investigations, one covering flame hardened armor[5] and the other, face hardened plate made by the pluramelt process[6], the examination of face hardened plate during this interval was limited to carburized plate. The latter was the only type of face hardened plate that achieved commercial importance. Plates made by the pluramelt process were used to a limited extent only, and flame hardening was never applied to production armor.

Again, as in the case of rolled armor during this period, there was little gain in knowledge regarding the characteristics of carburized plate that were considered desirable to achieve good ballistic behavior. The same factors previously found responsible for poor quality carburized plate in the 1938 report[7] on "Correlation of Microstructure and Ballistic Properties of Armor Plate, Part II, Face Hardened Plate" were found to be the cause of back spalling during ballistic limit and projectile-through-the plate- tests of failing plates that were examined metallurgically[8].

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1. Appendix A, Reports Nos. 7 and 85; 10 and 34; 70 and 71; 81 and 82; 105, 106, 107.
2. Appendix A, Reports Nos. 91, 100 and 102.
3. Appendix A, Report No. 105.
4. Appendix A, Reports Nos. 105, 106, 107; and 109, 110, and 111.
5. Appendix A, Reports Nos. 5 and 42.
6. Appendix A, Report No. 108.
7. Appendix A, Report No. 2.
8. Appendix A, Report Nos. 9 and 35, 12 and 37; 76 and 79 and 80.

(These plates covered the thickness range 5/8" to 1-1/2".) To emphasize the above ballistic-metallurgical correlation, several of the experimental reports issued prior to 1940 were redistributed as subcommittee reports[1]. The latter reports brought out one factor not previously mentioned in this wr_teup, namely the superiority in ductility possessed by carburized plate fabricated from a steel having the approximate analysis 0.20% C, 5.0% Ni, and 0.30% Mo compared to the ductility possessed by the higher C, Cr-Mo-V steel generally in use prior to 1939. This was attributed at least in part to the lesser amount of grain boundary carbides detected in the cases and cores of the plates made from the Ni-Mo steel. Improved resistance to penetration performance was also attributed to the former analysis as a result of a survey[2] of the ballistic limits of all face hardened armor tested at Aberdeen in the period 1938 to March 18, 1940.

The examinations performed at this time showed the desirability of having case depths extending in to 20/25% of the total plate thickness, lighter case depth giving rise to low ballistic limit[3] and excessive carburizing depth causing poor ballistic ductility[4]. Decarburization was revealed to be an evil, since its presence in the case gave rise to low ballistic limit[5] and its presence in the rear face was liable to cause erroneous hardness determination[6].

In 1940 the Ordnance Department foresaw the need for a method of armor fabrication capable of producing components of tanks and other armored vehicles in much greater quantity than could be realized by riveted or welded construction. The answer appeared to be cast armor. With the establishment in September 1940 of the Subcommittee for Cast Armor, the development of this type of armor proceeded rapidly.

Among the first reports distributed to the members of the Cast Armor Subcommittee was one[7] dealing with the correlation of ballistic properties and Brinell hardness versus thickness of cast armor plate. The report covered all the cast plates whose ballistic data were listed in the Aberdeen Proving Ground Reports on experimental and production plate issued in the period from March 18, 1940 to December 11, 1940. This comprised a total of 119 plates, ranging in thickness from 3/8" to 3", some of which had passed the then current specifications and the rest of which had failed.

The conclusions were as follows:

1. Appendix A, Report Nos. 40, 49, 50, 57, and 95.
2. Appendix A, Report Nos. 6 and 101.
3. Appendix A, Report No. 76.
4. Appendix A, Report Nos. 79 and 80.
5. Appendix A, Report Nos. 8, 36, and 76.
6. Appendix A, Report Nos. 70 and 71; 81 and 82.
7. Appendix A, Report No. 19.

"1. In good quality plate, the Brinell hardness decreases with increasing thickness; or, as the caliber of the shot is increased, the Brinell hardness must be decreased to secure optimum ballistic properties.

"2. The ballistic limits of homogeneous cast plate 1" and 1-1/2" thick are about the same as those of face hardened cast plate.

"3. The trend of the increase in ballistic limits of ductile plate with increasing thickness can be seen readily from figures 2, 3, and 4." (Author's note: This increase is very rapid.)

For a long time the concepts expressed in conclusion (1) above were the guide of armor plate metallurgists in their thinking concerning the desirable relationships among the factors hardness, plate thickness, and projectile caliber.

Among the first Cast Armor Subcommittee reports were several[1] which described the results of ballistic testing of cast turrets, cast turret base rings, and cast tank hull components at Aberdeen Proving Ground. Resistance to the shock impact of matching and overmatching A.P. Projectiles was revealed to be poor generally and upon finding similar behavior being exhibited by succeeding ballistically tested parts of tanks made from cast armor, samples of some of the latter were forwarded to Watertown Arsenal for metallurgical analysis[2]. Also subjected to metallurgical investigation during this period were a cast turret[3] which had been found to possess satisfactory ballistic properties and several ballistically tested experimental plates[4] that provided variations in hardness and resistance to ballistic shock. Further valuable data were provided by a Canadian cast armor medium tank top hull[5] which showed good penetration and shock resistance and by the ballistic test of a light tank cast armor base ring[6] which had been redrawn to a Brinell hardness of 255 after having first been heat treated to the prevailing hardness level. Excellent ballistic ductility was revealed by the redrawn base ring, which had been submitted after similar type base rings, in three turrets tested previously, that had higher Brinell hardness (302-340) had broken up badly under shock impact.

Perhaps because of the poor resistance to shock exhibited at Aberdeen by the pioneer tank armor castings, the emphasis at this time in the ballistic evaluation of the characteristics of cast armor was placed mainly on shock resistance. This situation has continued until today and has been justified by the Ordnance Department on the basis of structural

1. Appendix A, Report Nos. 15, 25, 27 and 29.
2. Appendix A, Report Nos. 58 and 62; and 63.
3. Appendix A, Report Nos. 86 and 87.
4. Appendix A, Report Nos. 65 and 68; and 103. The examination of some of the experimental plates were not written up individually but were included in Cast Armor Subcommittee Report No. 30 (Appendix A, Report No. 94)
5. Appendix A, Report No. 64.
6. Appendix A, Report No. 66.

integrity, for the cast armor of tanks not only provides protection against enemy firepower but also constitutes a vital portion of the structural framework.

In November 1941, most of the cast armor metallurgical investigations conducted to date were summarized in a report[1] distributed to the members of the Cast Armor Subcommittee. The report contained the ballistic and metallurgical data for fifteen (15) samples of armor, most of which were within the thickness range of 1" to 2-3/4". The tests used to derive the metallurgical data consisted of radiographic examination, chemical analysis, Brinell hardness, tensile tests, macroscopic examination, and microscopic examination. Results were stated as follows:

"1. There is a correlation between metallurgical properties and ballistic properties of cast armor.

"2. Good quality cast armor should possess sufficiently low hardness to permit satisfactory ballistic performance, have a uniform sorbitic structure, and should have a minimum amount of porosity and dendritic segregation. (Author's note: By sufficiently low hardness was meant approximately 250 Brinell for the 1" to 3" thickness range).

"3. Excessive amount of non-metallic inclusions of fairly large particle size in themselves have not been found to be responsible for failure.

"4. Generally speaking marked dendritic segregation is undesirable. Pronounced dendritic segregation associated with relatively high hardness may be responsible for failure.

"5. In some cases, pronounced porosity as revealed by X-Ray examination in plates of normal hardness did not cause failure, but when present in castings having a relatively high hardness, failure occurred.

"6. In two cases porosity in critical areas (improper fillets) which was revealed by macroetching but not by X-Ray contributed to the failure of the casting.

"7. Castings having an A.S.T.M. grain size of No. 5 and of the proper hardness have been found to possess good shock resistance.

"8. In several cases, castings having a grain size of A.S.T.M. No. 1 and having short internal cracks and some segregation failed under shock.

"9. Good quality armor plate castings having high ballistic properties generally possess a sorbitic structure with a minimum amount of ferrite.

1. Appendix A, Report No. 94.

"10. Grain boundary carbides have been found in some of the defective plates."

Miscellaneous other investigations of cast armor at this time included flame hardening (which never was in production); the ballistic effects of fine surface cracks revealed by magnaflux[2] (it was decided that such cracks were not necessarily cause for rejection); and a correlation[3] of ballistic properties and chemistry of plates within the thickness range 1-1/4" to 2-3/4". The latter investigation indicated that plates of different analysis, having the same hardness, differed somewhat in resistance to penetration. (The maximum difference was approximately 150 feet/second).

C. Development of Low Alloy Armor

The compositions from which homogeneous rolled plate was made prior to 1940 were relatively high in both alloy and carbon content. A favorite analysis ranged approximately as follows:

C	Mn	Cr	Ni	Mo	V
.30/.55	.40/.70	1.10/1.40	—	.40/.80	.20/.30

The increase in the production of heavier gauge homogeneous rolled armor after 1939 (from a maximum thickness of 1" prior to 1940 to up to 1-1/2" plate by 1942) saw a reduction generally in the carbon content to .25/.30, in order to achieve better weldability, and a substantial decrease in the vanadium content. However, there was an accompanying increase in the total amount of alloying elements. An analysis in use by one of the major rolled armor producers contained approximately:

C	Mn	Cr	Ni	Mo	V
.18/.23	.40/.60	.05/.10	4.85/5.00	.25/.30	.03/.10

and in other production analyses the maximum alloy contents were as high as:

Cr	Ni	Mo
1.60	4.35	.70

Carbon and alloy contents of the first production cast armor were relatively high also. The compositions of the samples surveyed by November 1941 Ballistic Metallurgical Correlation Report[4] were within the ranges:

C	Mn	Cr	Ni	Mo	V
.21/.53	.48/1.32	.72/3.80	0.0/3.39	.36/.68	0.0/.21

1. Appendix A, Reports Nos. 13 and 38
2. Appendix A, Report No. 74
3. Appendix A, Report No. 72
4. Appendix A, Report No. 94

By early in 1942, carbon had been decreased to approximately .25/.35 in order to minimize the danger of quench cracking as well as to facilitate welding, and vanadium had been eliminated by all cast armor manufacturers with the exception of one. At this time the analyses of the various cast armor producers fall within the following ranges of maximum chemistry (i.e., using the element Mo for illustration, the maximum amount of this element in the analysis of one producer was .40%, of another producer, .90%, and of each of the other producers, between .40% and .90%):

C	Mn	Ni	Cr	Mo	V
.25/.35	.65/1.00	0.0/2.50	1.10/3.00	.40/.90	0.0/.05

As early as 1940 Watertown Arsenal had visualized that the day might come when it would be necessary to utilize compositions low in strategic alloying elements, and studies[1] had been initiated on homogeneous rolled plate to determine the ballistic and metallurgical properties of low alloy armor. Initial results[2] with 1-1/2" rolled plate, tested for resistance to penetration, were satisfactory and by November 1941 a .40 C, Mn-Mo composition had been developed that in the 1-1/2" gauge not only had a ballistic limit in excess of the current specifications but exhibited good ballistic shock resistance as well[3]. Moreover, it was concluded from a program conducted on 1/2" rolled plates[4] that "The ballistic properties of the compositions containing high percentages of strategic elements do not surpass those of the low alloy compositions when heat treated to approximately the same hardness range".

In February 1942 what Watertown Arsenal had foreseen became a reality; the armor subcommittees were notified by the War Production Board of expected scarcities of nickel, chromium, and vanadium for use in cast and rolled armor. Plans were immediately made for the development of low alloy compositions capable of meeting the current ballistic specifications. Experimental compositions were selected on the basis of the alloy restrictions and the small amount of data on low alloy analyses which had been obtained at Watertown Arsenal and by the armor producers. During the months of March and April several hundred cast and rolled homogeneous test plates of 1", 1-1/2" and 2" thickness were manufactured and heat treated and then ballistically tested at Aberdeen. Each plate was given a complete ballistic test (shock, PTP, and penetration) unless failure occurred on the shock test, which in the majority of cases was applied first. In addition to the standard 75 mm. T12 AP shock test at 25° obliquity applied to the 1-1/2" and 2" thicknesses, plates which withstood this test in some cases were tested with the 75 mm. MK1 15 pound Proof Slug at normal impact. The shock test of the 1" armor consisted of a 37 mm. M51 AP projectile impacting at 25° obliquity. Following the ballistics, numerous samples of armor that had performed satisfactorily according to the specifications were forwarded to Watertown for metallurgical examination and weldability tests.

1. Appendix A, Report No. 14
2. Appendix A, Reports Nos. 14 and 24
3. Appendix A, Reports Nos. 98 and 99
4. Appendix A, Report No. 97

The development of low alloy cast armor between February and May 1942 was reviewed during the latter month in an experimental report[1] based on just the results of the ballistic tests. Among the conclusions were the following that are applicable to this writeup:

"1. Results on the experimental plates indicate that the shock resisting properties of the new low alloy compositions will be reasonably comparable to those of the old, higher alloy nickel-chrome-molybdenum and chrome-molybdenum steels.

"2. Vanadium requirements for cast armor have been eliminated entirely.

"3. Chromium contents have been reduced from a maximum of 3% to a maximum of .60%.

"4. Nickel contents have been reduced from a maximum of 2.50% to a maximum of .60%.

"5. The molybdenum contents of the new analyses are in general less than in the old compositions.

"6. The average manganese content of the new compositions is higher than in the case of the old compositions. (Author's note: Reduction in nickel and chromium was compensated for by increase (up to about 1.50% maximum) in manganese, which was not a critical element.)

"7. Present indications are that the margin of excess on ballistic limit will be adequate for the low alloy compositions although slightly inferior to the old analyses."

That alloy content could be substantially reduced while retaining good ballistic properties was also found to be true for rolled armor. (This information was evident from the Aberdeen firing record reports. No report similar to the above for cast armor was written.) As a result of the low alloy program, by November 1942, the analyses of all the rolled armor producers were down to within the following ranges for all plate thicknesses:

C	Mn	Cr	Ni	Mo	B	Zr
.25/.26	.85/1.65	0.0/.75	0.0/1.0	.20/.42	0.0/.002	0.0/.088

The low alloy armor samples received at Watertown represented twenty-eight cast armor test plates of 1", 1-1/2", and 2" gauge and fourteen 1-1/2" rolled test plates. Since the results of chemical analysis, tensile tests, and Izod tests were reported by the Armor producers, these tests were not performed at the Arsenal. Metallurgical examination

1. Appendix A, Report No. 117

consisted of Brinell hardness determination, macroetching, determination of grain size by microscopic means and by use of the Shepherd fracture test, microscopic examination, and, for the first time, hardenability determination, by means of the Jominy bar. The initial use of the latter test for the evaluation of armor plate was a significant milestone along the road to true understanding of the correlation between ballistic and metallurgical characteristics of armor.

A few remarks concerning how Jominy hardenability was evaluated in terms of armor plate are appropriate at this point. The criterion of "adequate hardenability for thorough hardening" was the presence of at least a 50% martensitic (or half hardened) microstructure at the center of the as quenched armor plate, which, it was believed, corresponded to the hardness midway between the highest and the lowest hardness in the Jominy bar of the same steel, austenitized similarly to the plate. Based on correlations between this hardenability criterion and the amounts of ferrite seen at the centers of the sections in the samples of cast and rolled low alloy test plates, it was concluded that a 50% martensite structure would be essentially free of ferrite. A microstructure free of ferrite was deemed to be "thoroughly hardened". The above criterion was used in all the reports written on the development of low alloy armor.

The significant data contained in the two reports[1] covering the metallurgical examinations are itemized below:

1. The hardness ranges of the cast and rolled test plates examined were 197-294 Brinell and 229-326 Brinell, respectively. These hardness ranges must be kept in mind when considering the data and conclusions described below.

2. Much ferrite was detected in the microstructures of many of the plates, both cast and rolled. It was, therefore, concluded for cast armor that: "The ability of a certain composition to harden completely through upon quenching in a given thickness is not a requisite for satisfactory ballistic performance. In general, however, higher ballistic efficiencies are obtained when thorough hardening results." For rolled armor it was stated: "On the basis of the data compiled from the limited number of plates studied, it is not possible to draw conclusions between hardenability and ballistic performance. It is noted, however, that two Disston plates did give satisfactory results although having poor hardenability. (Author's note: By ballistic performance in this paragraph is meant resistance to shock primarily.)

3. Grain boundary carbides in varying sizes and amounts were found in many of the cast and rolled plates. The conclusion was, therefore, that the size, shape, and distribution of the carbides had no relation to the ballistic

1. Appendix A, Reports Nos. 114 and 118

performance of cast and rolled plates. In almost all metallurgical investigations conducted thereafter, the effect of grain boundary carbides was felt to be of minor importance and tests to determine their presence were applied only occasionally.

4. Interdendritic chains of nonmetallic inclusions were found in some of the cast plates while long inclusion stringers were revealed in some of the rolled armor. It was, therefore, concluded that the size, shape, and distribution of the nonmetallics in cast and rolled plate do not cause failure. (Author's note; Failure here refers primarily to behavior during the projectile-through the plate test. The inadequacy of the microscope in determining nonmetallic content of rolled plate was not recognized at this time.)

5. Some of the rolled plates possessed severely banded microstructures. This led to the conclusion that: "The intensity of banding also has no apparent relation to ballistic performance."

6. Grain sizes varied from A.S.T.M. No. 5 to finer. No conclusions were made about grain size.

It should be noted that in regard to resistance to ballistic shock the conclusions for 1-1/2" and 2" plates were derived from only the results of the 75 mm. AP obliquity test. Insufficient plates that had been shock tested with the 75 mm. slug were examined to be able to evaluate these results. The latter test is appreciably more severe than the former.

Chemical composition was correlated with ballistic performance again in June 1942 by a report[1] which surveyed one hundred and forty-five cast low alloy test plates ranging from 1-1/2" to 2" in thickness, most of which had been subjected to the 75 mm. slug. Pertinent conclusions are given below:

"All of the low alloy cast compositions have comparable ballistic excesses over the specifications for both one and one-half and two-inch sections.

"There is considerable evidence that when the chemical composition is such that the steel has insufficient hardenability for the section size, the plate will generally have poor resistance to the shock of a 75 mm. MK1 slug."

1. Appendix A, Report No. 119

This was the first report to point out that "inadequate hardenability" caused ballistic shock failure, a fact that was elaborated on and emphasized over and over again thereafter.

Shortly afterwards four 1-1/2" cast plates and one 2" cast plate that had failed the 75 mm AP shock test were received for metallurgical investigation. Much more ferrite was detected in their structures than had been seen in the plates previously studied and from consideration of their Jominy hardenability it was concluded[1] that "Failure of the five plates is due to insufficient hardenability for the section size and severity of quench, resulting in microstructures containing excessive quantities of free ferrite." Chains of elongated interdendritic inclusions, segregated areas very high in nonmetallic content, entrapped slag particles, and numerous interdendritic oxide films, caused by poor steel making and deoxidation practices, were also found in one of the 1-1/2" plates and listed as a probable contributory cause of failure.

With the revision of the cast armor specifications in August 1942, which increased the shock test striking velocities and thus made the test more severe, it became necessary again to summarize the development of low alloy cast armor. By December 1942 ballistic and metallurgical data (i.e., chemical composition; tensile, Brinell, and Izod test results; and heat treatment details - all supplied by the producers) had been accumulated for two hundred and twenty plates and analyzed[2], giving the following pertinent information:

> "a. The data are inconclusive with respect to an optimum Brinell hardness range for cast armor in thicknesses of 1-1/2 to 2 inches. In general, it may be said that the excess of ballistic resistance increases with Brinell hardness up to some maximum Brinell value in the neighborhood of 290-300. The top limit will vary with the chemistry of the steel, its quality, and its heat treatment. At higher hardnesses than this limit, the penetration characteristics change to a "plugging type" of failure and the accompanying possibility of a considerably lower ballistic efficiency. These conditions are all dependent, of course, upon the caliber of the projectile or more adequately expressed, the ratio of the plate thickness to projectile diameter. Certain producers obtain a comparable excess at higher hardnesses. These differences are not thoroughly understood, but probably arise from the higher ductility of the softer material and the consequent greater degree of bulging on the back which can take place before a 'complete to light' is formed.

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1. Appendix A, Report No. 122
2. Appendix A, Report No. 126

"b. With respect to shock resistance versus Brinell hardness, no generalities can be drawn. However, given a steel of good quality which will harden through upon quenching, it has been demonstrated that superior shock-resisting characteristics can be retained up to a hardness of 290 Brinell. On the other hand, repeated shock failures have occurred on material at a Brinell hardness level of approximately 230 when inadequate hardenability was present or the material had not been effectively quenched. The most satisfactory range under average conditions from both the shock and penetration standpoints appears to be 240-260 Brinell."

In order to determine in a direct manner why cast test plates of producers whose armor generally was satisfactory would sometimes fail the revised velocity slug test, passing and failing plates made by several companies were subjected to Brinell hardness surveys, macro-etching, microscopic examination, and the Jominy hardenability test. Data obtained by chemical analysis, tensile tests, and Izod tests were furnished by the producers. From this investigation[1] the following conclusions were drawn:

"Shock failures in 1-1/2" and 2" armor, subjected to the slug test, are largely attributable to either poor steel quality, low hardenability, poor quenching practice, or a combination of these factors. Failure because of low hardenability or an insufficiently drastic quench is generally associated with the presence of an excessive amount of ferrite."

The investigation report also brought attention to the role that carbon and alloy segregation played in causing decrease in hardenability in the dendritic axes and therefore promoting the occurrence of free ferrite at these locations.

It is well at this stage to recapitulate a bit and point out some of the deficiencies in the existing knowledge relating to the correlation between metallurgical properties and resistance to ballistic shock. Although shock failures of cast and rolled armor could be attributed in most cases to microstructures containing large amounts of ferrite, there was no understanding of the mechanism whereby the presence of the ferrite imparted this undesirable condition to the armor. There was no correlation between any physical property of the armor and its ballistic shock behavior, with the exception of hardness. Attempts to correlate ductility and toughness, as measured by the tensile test, with the quantity of ferrite in the microstructure and with ballistic shock resistance were unsuccessful for both rolled and cast armor. The above was true not only for tensile test results reported by the companies (which were open to doubt as to whether or not they were actually representative of the plates) but also for tensile tests conducted at Watertown. Likewise, very surprisingly, room temperature Izod test data reported by the cast armor

1. Appendix A, Report No. 128

companies did not explain the ballistic behavior of the corresponding test plates. This apparent anomaly was later discovered to have been caused by the assumption that the coupons from which the Izods were machined (the coupons were 1-1/4" to 2" square by approximately 6" long and were either cast as prolongations on the test plates or were separately cast) had the same physical properties as the corresponding plates. Actually, because of their smaller dimensions, the coupons were quenched more efficiently.

When early in 1943 a correlation was attempted between room temperature Izod values and the ballistic performance of 4-6" thick cast armor, excellent results were attained. Whether the tests were conducted upon pieces machined from the plates or upon separately heat treated test coupons poured from the same heat as the armor sections is unknown, but in either case the chances that the physical properties determined near the edges of plates or from coupons will be representative of the plates are much greater for 4-6" thick armor than for plates that are only 1-2" in thickness.

To illustrate how inadequate was the criterion of ferrite content for explaining ballistic shock behavior, because little free ferrite was seen in the microstructure of an 1½" high alloy cast plate[1] examined during the early part of the low alloy development program, the failure of the plate when impacted by a 75 mm. slug was erroneously attributed to poor steel quality. It was not until the development of the Fibre Fracture Test and the utilization of low temperature V-notch Charpy tests in 1943 that the effect of microstructure upon impact toughness was really understood. It was learned then that pearlitic and bainitic microstructures imparted poor impact toughness to steels, pearlitic structures having a more detrimental effect than bainitic structures, and that a steel could show little or no free ferrite and still possess poor shock resistance because the microstructure consisted of intermediate or low temperature transformation products (i.e. a bainitic structure). A tempered martensitic structure was found to produce optimum impact toughness at all hardness levels.

D. Low Temperature Testing Program

During the months of January and February 1943, ballistic tests, in accordance with the specifications current then, were conducted upon cast and rolled armor plates, 1", 1½", and 2" in thickness; armor structures; and armor weldments at the Ordnance Department Winter Detachment, Ordnance Proving Center, at Camp Shilo, Manitoba, Canada. The temperatures of the armor varied between -15 and -35°F. during the period of testing. A very large proportion of the cast armor failed in a brittle fashion when subjected to the required slug shock tests (75 mm. for the 1½" and 2" plates and 37 mm. for the 1" plates, all at normal obliquity), numerous plates breaking into several pieces. Rolled armor behaved, in general, more satisfactorily than cast armor at low temperature when subjected to ballistic shock (Normal obliquity 75 mm. slug for the 1½" and 2" plates and

1. Appendix A, Report No. 121.

37 APC at 25° for the 1" plates). An increased tendency to backspall was, however, noted in several rolled plates at low temperature as compared to similar plates manufactured by the same companies but tested at room temperature.

In March, 1943 all pertinent data regarding the plates tested at Camp Shilo were analyzed at Watertown Arsenal and the results were distributed in the form of cast and rolled armor subcommittee reports[1]. It was concluded that in most cases the poor shock resistance at reduced temperatures was traceable to either inadequate hardenability or poor quenching practice, resulting in the precipitation of ferrite during hardening.

Sections from thirty (30) cast and seventeen (17) rolled plates from the Shilo Cold Test Program were examined at Watertown Arsenal. The results of the experimental work conducted at this arsenal were published in two reports, one covering cast armor[2] and the other rolled armor[3]. Good correlations between the ballistic and metallurgical properties of cast armor were obtained by employing the Brinell hardness test, chemical analysis, macroetching, microscopic examination, and the newly developed Fibre Fracture Test and V-notch Charpy impact tests. Likewise, the same tests, with the addition of Jominy hardenability tests and the newly developed Fracture Test for Steel Soundness, gave good correlation between the ballistic and metallurgical properties of rolled armor.

Conclusions drawn from the metallurgical examination of the cast armor sections are as follows:

> "1. A low temperature (-10° to -40°F.) ballistic shock test of 1" to 2" cast armor is much more severe than the same test conducted at normal temperatures, all other factors remaining constant. This increase in the severity of test reveals the poor shock characteristics of borderline quality armor.
>
> "2. Poor performance of 1" plates is associated with heterogeneous microstructures (high temperature transformation products), a high hardness level, or both. Properly heat treated low alloy cast steel of the type studied should not be over approximately 330 Brinell. The heterogeneous structure was generally caused by an insufficiently drastic quench and an incomplete utilization of the alloy.
>
> "3. The most important cause of the poor performance in the 1½" and 2" cast plates examined was the presence of heterogeneous microstructures formed as a result of incomplete quenching, insufficient hardenability or a combination of both factors. Many of the plates could be improved materially with an improvement in the quenching technique.

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1. Appendix A, Reports Nos. 129 and 130.
2. Appendix A, Report No. 137.
3. Appendix A, Report No. 188.

However the alloy content of several of the heats is insufficient to impart enough hardenability to completely quench out 2" plates even if a drastic quench is employed.

"4. The metallurgical tests which may be used to indicate the presence of heterogeneous structures and the resulting poor shock properties of incompletely quenched cast armor are the fracture test, V-notched Charpy impact test, and the microscopic examination."

Heterogeneous microstructures which imparted poor impact properties to the steels were also found to be responsible for the poor performance at Shilo of an M4 tank cast turret[1] and a bow machine gun casting from a Cadillac light tank, M5[2].

Pertinent conclusions listed in the report covering the metallurgical examination of the rolled armor samples are as follows:

"1. The ballistic shock and projectile-through-the plate tests for 1" to 2" rolled armor at subnormal temperatures (-15°F. to -35°F.) are much more severe than the same tests conducted at room temperature, and whereas impact toughness, steel soundness, and Brinell hardness of a plate may be adequate for satisfactory performance at room temperature, at low temperatures a similar plate with respect to these characteristics may be unsatisfactory ballistically.

"2. Based upon the study of the sixteen (16) rolled homogeneous plates examined, it can be stated that the following characteristics are necessary in rolled armor of 1", 1½", and 2" thicknesses to pass specification requirements consistently at low temperatures:

a. Shock Test

(1) Optimum Impact Toughness - The armor must have sufficient hardenability and be quenched efficiently so that it will be completely or almost completely quench hardened throughout the section, thereby possessing, after proper tempering, optimum impact strength at high rates of strain. This is required regardless of composition; the presence of appreciable nickel is not sufficient to overcome the deleterious effects of non-martensitic constituents.

(2) Proper and Uniform Hardness - Quenching and tempering operations must be so conducted that the plate in the finished condition will have proper and uniform hardness throughout the section.

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1. Appendix A, Report No. 142.
2. Appendix A, Report No. 146.

(3) Good Steel Soundness - The steel must be free of excessively long stringers or concentrations of inclusions.

b. Projectile-Through-the Plate Test

(1) Good Steel Soundness - The degree of steel soundness must be greater than that tolerated in armor subjected only to room temperature testing. The armor must be relatively free of long inclusion stringers or concentrations of non-metallics into planes of weakness; the data indicate that the steel soundness rating of plate in thicknesses above as well as below 1-1/8" must be superior to "D".

(2) Proper Hardness - The lower the testing temperature the softer the plate must be to resist spalling. The upper hardness limits for the various thicknesses cannot be stated definitely from this investigation.

"6. By application of hardness tests, the Fracture Test for Steel Soundness, and the Fibre Fracture Test, the suitability of armor for use at low temperatures can be evaluated.

"7. Low temperature Charpy tests are superior to the Fibre Fracture Test for determination of complete quench hardening at all Brinell Hardness levels.

"8. Rockwell "C" 43 has been shown to be unsuitable as a criterion of hardenability, and a new method based on attainment of fibre has been introduced." (Author's note: Following the examination of a series of heavy cast armor gun shields[1] in the middle of 1943, the hardenability criterion was changed from that originally selected as a result of the low alloy program. The new criterion was Rc 43, for it had been found that when the gun shields had been quench hardened to at least this value, following tempering fibrous fractures resulted. Later, irregularities occurred when this criterion was used, and in this report the explanation was revealed. It was shown that Rockwell "C" 43 (or 400 BHN) could correspond to variance in microstructure from 100% martensite to 0% martensite, and it was suggested that an as quenched hardness be selected that would, upon tempering, result in fibrous fractures. It was also pointed out in this report that to insure the occurrence of optimum impact toughness at all hardness levels the armor should be hardened to give a structure containing as little nonmartensitic products as possible.

1. Appendix A, Report No. 132.

E. Evaluation of 1" to 2" Production Cast Armor

With the introduction of the Fibre Fracture Test, it became possible for the Armor Section to evaluate fairly accurately individual castings as well as the larger numbers required heretofore when even a qualitative statistical evaluation was difficult. It became possible for The Proving Center, Aberdeen to conduct ballistic tests on plates or on components of armored vehicles and then obtain a fairly accurate evaluation of the metallurgical properties by submitting samples to the Armor Section. For example, armor which exhibited inconsistencies were submitted to this arsenal for examination, and in the studies[1] made it was possible to evaluate the toughness by means of the fracture test and V-notch Charpy impact tests, and generally this information was sufficient to determine the cause of inferior ballistic performance in specific test plates or in other cases to evaluate the merits of a new type ballistic test. In most of these studies additional tests were conducted to determine the cause of inferior armor in order to aid the manufacturer in improving his product. The inferior toughness which was generally responsible for the shock type failures was attributed for the most part to incomplete transformation to martensite upon quenching or temper embrittlement. The temper embrittlement was investigated by retempering specimens (at a temperature above 1100°F. but not so high that softening would result) followed by a water quench. An improvement in the toughness would indicate temper embrittlement in the steel in the "as received" condition. However, if the toughness was not raised to a satisfactory value at the subject hardness, the steel was reheat treated in small sections to the same hardness using good heat treating practice. The impact values then obtained could be compared with the original values to see if any improvement was obtained. As time went on it was possible for the Armor Section to draw a curve of hardness versus optimum V-notch Charpy impact values, and the values were used to compare the results on subsequent samples.

The metallurgical examinations[2] of components of experimental armored vehicles have generally been conducted to insure that the ballistic performance characteristics were being obtained on armor of acceptable metallurgical properties so that the performance of armored vehicles composed of satisfactory armor structures of the same design would be known providing the toughness specification requirements were exceeded. At the same time the Armor Section was able to learn the properties of the production armor being manufactured so that it could direct its more fundamental research along the channels requiring the most urgent and fruitful study.

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1. Appendix A, Report Nos. 200, 218, 229, and 238.

2. Appendix A, Report Nos. 145, 154, 213, and 233.

F. Effect of Hardness on Ballistics

It will be recalled that in an earlier section of this report conclusions of a report written in January, 1941 on the "Correlation of Ballistic Properties and Brinell Hardness vs. Thickness of Cast Armor Plate"[1] had been listed, and it had been stated that "For a long time the concepts expressed in Conclusion (1) above were the guide of armor plate metallurgists in their thinking concerning the desirable relationships among the factors hardness, plate thickness, and projectile caliber." Conclusion (1) of the report was as follows:

> "1. In good quality plate, the Brinell hardness decreases with increasing thickness; or, as the caliber of the shot is increased, the Brinell hardness must be decreased to secure optimum ballistic properties."

This section will explain more fully the second part of the above conclusion and will show further that Brinell hardness need not be decreased with increasing thickness providing that good impact toughness can be attained. The effect of high Brinell hardness on resistance to penetration and on resistance to shock will be explained also.

In February, 1941 an analysis of Aberdeen letter reports[2] had indicated that for 1/2", 3/4", and 1" rolled homogeneous plate, penetrated by undermatching projectiles, ballistic limit increased with hardness up to at least 400 BHN. But since armor of machineable quality was desired, a Brinell range of 285 to 335 was recommended for inclusion in the specifications. A year later the same effect was discovered for 1/4 rolled homogeneous plate[3] but was ignored so far as change in specification requirements was concerned.

The first program designed to learn, among other things, the effect of various hardnesses on resistance to penetration was conducted at this arsenal during the latter part of 1942. Rolled homogeneous plates of 3/8", 1/2", 5/8", 3/4", and 1" thickness and varying in hardness to as high as either 388 or 415 BHN were tested. The pertinent conclusions drawn were as follows:

> "2. Under fire of caliber .50 AP M2 projectiles, while the ratio of plate thickness to projectile diameter (e/d is greater than .83, resistance to penetration increases with increasing plate hardness until spalling effects a decrease in effective plate thickness.
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> "4. There is a critical range of hardness (BHN 360 to BHN 400) for plates in the thickness range 3/8" to 1" above which resistance to spalling breaks down under impact with caliber .50 AP M2 projectiles. Within this blanket range, a specific range, in inverse correlation with thickness, exists for each plate thickness.

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1. Appendix A, Report No. 19.
2. Appendix A, Report No. 33.
3. Appendix A, Report Nos. 106 and 107.

"5. Inasmuch as resistance to penetration increases with plate hardness, the critical hardness range cited above will define the maximum hardness which will impart optimum simultaneous resistance to spalling and penetration."

The only metallurgical tests conducted upon the plates were Brinell hardness and tensile tests.

About the middle of 1943 an "Effect of Hardness on Ballistics" program was inaugurated at Aberdeen Proving Ground for both cast and rolled plates. The purpose of the program was to determine the effect of hardness on the resistance to penetration of all production thicknesses of armor, when penetrated by undermatching, matching, and overmatching projectiles. Specification shock tests were to be applied also, and the hardness giving the best combination of resistance to penetration and resistance to shock was to be determined for each plate thickness.

The first armor tested consisted of several series[1] of 1" cast plates. Upon completion of the firings, a sample was cut from each plate and sent to Watertown for metallurgical examination. Here the armor was subjected to hardness and fracture tests as well as other tests. It was soon apparent that the armor generally had poor impact toughness at hardnesses above 320 BHN and therefore could not be used to ascertain the effect of hardness only on ballistics. With the appearance of crystallinity in the fractures at hardnesses above 320 BHN both resistance to penetration by undermatching projectiles as well as by matching projectiles and resistance to shock were found to decrease. The poor impact toughness of the 1" cast plates was attributed to combinations of poor steel quality and poor microstructure.

Attempts to evaluate cast armor of 2" thickness were discontinued following the testing of one series[2] of plates, which was found at Watertown to give crystalline fractures at hardnesses above 240 BHN.

The Aberdeen "Effect of Hardness on Ballistics" program conducted on rolled plate was more successful, and all production thicknesses, ranging from 1/4" to 4" were investigated. The first metallurgical examination[3] of rolled plate samples from this program was conducted in November 1943. Examination at that time and thereafter for all the samples of the program included at least hardness, the Fibre Fracture Test, and the Fracture Test for Steel Soundness. Other tests performed on most of the samples included chemical analysis, macroetching, microscopic examination, Jominy hardenability, and the V-notch Charpy test.

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1. Appendix A, Report Nos. 131, 144, 152, 157, and 170.

2. Appendix A, Report No. 200.

3. Appendix A, Report No. 149.

Fibrous fractures at all hardness levels were found in the first three sets of plates examined[1]. Crystallinity at high hardness was first encountered in the next series examined[2], which consisted of 3/4" plate. The material showed crystalline fractures at hardnesses above 330 BHN. This was a new phenomenon and it was stated that "It is felt that this lack of ductility in the fracture test is not associated with an improper heat treatment but rather is a function of the hardness for this composition when efficiently heat treated under production conditions."

The cause of crystallinity at high hardness was not correctly stated in the reports covering the examinations of the "Effect of Hardness on Ballistics" samples[3] until June, 1944. Because of work done at Battelle Memorial Institute plus work in progress at Watertown, the occurrence of crystallinity at hardness above 340 BHN in a series of 1" plates[4] was at that time attributed to temper brittleness. This is temper brittleness which results from tempering within the embrittlement range (approximately 650°F. to 1100°F.), as differentiated from the temper embrittlement encountered in heavy cast armor due to slow cooling, from the tempering temperature, down through the embrittling temperature range.

The inability of rolled armor to fibre at all hardness levels was attributed to temper brittleness in the succeeding reports[5] written on plate examined for the "Effect of Hardness on Ballistics" project. It was found that for most of the production armor tested by the program, the thicker the armor, the lower the hardness level at which fibre could be attained. Except for one series of 1½" Republic plates, which fibred at 377 Brinell, the highest hardness of the series, plate thicker than 3/4" was found to give partly or wholly crystalline fractures at hardnesses above 360 Brinell. Thin plate, which was tempered for relatively short times, generally fibred at hardnesses as high as 415 BHN.

Correlation of the data obtained at Watertown with the Aberdeen firing results revealed that so long as a plate had good impact toughness, as revealed by a fibrous fracture, resistance to penetration by undermatching and matching projectiles increased with increase of hardness, and shock properties, as measured by the impact of a slug, were adequate at even the highest hardness levels. Poor resistance to penetration at high hardness levels when tested by undermatching and matching shot was found to be caused by poor impact toughness, as shown by the presence of crystallinity in the Fibre Fracture Test and not by the hardness itself.

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1. Appendix A, Report Nos. 149, 153, and 156.
2. Appendix A, Report No. 164.
3. Appendix A, Report Nos. 165, 173, 176, 181, 182, 184, and 185.
4. Appendix A, Report No. 186.
5. Appendix A, Report Nos. 187, 191, 192, 195, 198, 202, 203, 206, 208, and 210.

G. Development of Heavy Armor (3" and Over)

Cast Armor

In 1942, the use of heavy cast armor for both gun shields and tank protection was introduced. The thickness of tank armor was increased gradually to anticipate the changing tactical situation until, in 1944, the armor had increased to 6" at the front of heavy tanks. Gun shields, on the other hand, for 16" guns were made initially 4" and 6" thick. Consequently the problems of manufacturing and developing ballistic specifications were first encountered in the latter ordnance equipment.

A report[1] of the first group of gun shield sections submitted by The Proving Center, Aberdeen for examination at this arsenal revealed that the basic requirements of adequate heat treatment and microstructure were necessary in armor to obtain optimum ballistic properties in heavy sections as well as in the lighter gauge armor discussed previously. In this investigation it was observed that armor of nonmartensitic microstructure and consequently inferior impact properties exhibited structural failures (cracking) and/or back spalling when impacted with matching A.P. projectiles at 15° obliquity using a velocity designed to cause partial penetration in satisfactory armor. In this and in other investigations of heavy armor, some inconsistencies between the metallurgical and ballistic properties which were encountered may be attributable to variations in projectile performance because suitable A.P. projectiles over 3" in diameter which neither deform nor break up during penetration have yet to be developed. Nevertheless, a fairly good correlation was found between the results of the fibre fracture test and the ballistic results on the group of castings studied. One of the companies making gun shield armor castings used a 2.5% Cr, .5% Mo composition which was far superior to the 1.0% Ni, .5% Mo composition used by another manufacturer. Since there was very little tonnage production of this class of armor at the time, manufacturers were allowed considerable leeway in their alloy restrictions in order to foster improved gun shield armor. As a result the second manufacturer which preferred to develop compositions other than the 2.5% Cr, .5% Mo type tried instead several compositions containing up to 1½% of Mn, Cr, and Ni with .5% Mo and .1% V. This manufacturer continued to have considerable difficulty in producing gun shield armor having satisfactory ballistic properties and toughness.

Samples of this armor were examined[2] at this arsenal for hardenability (evaluated by measuring the amount of intermediate and high temperature transformation structures at various points on the Jominy bar) and impact properties after several types of heat treating cycles. The conclusions in this report were indecisive, but it was shown that even this relatively high alloy steel cannot be quenched to martensite in sections over 4" thick.

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1. Appendix A, Report No. 132.
2. Appendix A, Report No. 177.

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The manufacturing difficulties and inferior ballistic performance encountered in gun shield armor and in 3-4½" tank armor being developed in 1943 indicated the need for basic research on the heat treatment of higher alloy steels used in the heavier sections. The resulting studies[1] showed that temper brittleness which had first been recognized in modern American armor in a study[2] of December 1943 was the most important factor impairing the toughness of the high alloy, heavy armor.

Consequently, subsequent investigations[3] on heavy armor requiring a correlation between the metallurgical and ballistic characteristics were subjected to impact tests after retempering to ascertain the presence of temper embrittlement. Thus it was possible to evaluate the metallurgical properties of heavy armor and in inferior armor to determine whether the brittleness was caused by incomplete quenching to low temperature transformation products or by temper embrittlement.

The above studies played an important part in confirming the principle that high toughness in metallurgical tests is reflected in optimum ballistic properties, and as a result the impact test could be used as a non-ballistic acceptance test in the specifications for armor over 4" thick which cannot be given adequate ballistic tests at present.

Rolled Armor

Heavy rolled armor has not been considered a very important problem by the Ordnance Department because it has not been used very extensively in armored vehicles since they can be fabricated more quickly and at less expense with cast armor structures. Since the Ordnance Department has not requested many investigations of heavy rolled armor and the armor section has been kept busy with pressing problems in other types of armor, very few studies have been made on heavy rolled armor. The few investigations[4] that have been conducted on 2½" to 6" rolled armor and 3" to 5" face hardened armor have shown that the toughness and steel soundness as determined by the fracture tests and of course hardness are the important metallurgical factors in ballistic performance of heavy rolled armor just as toughness is necessary in heavy cast armor and toughness and steel soundness are important in rolled armor under 2" in thickness.

1. Appendix A, Report Nos. 205 and 212.
2. Appendix A, Report No. 160.
3. Appendix A, Report Nos. 193, 196, 204, 215, 216, 217, 219, 220, 223, 224, 225, 228, 232, and 234.
4. Appendix A, Report Nos. 180, 189, and 236.

H. Face Hardened Armor

As was mentioned in the introduction, before the war manufacturers were given the opportunity of making either face hardened or homogeneous armor as long as the ballistic requirements were exceeded. However, early in the war several conditions militated against the indiscriminate use of face hardened armor. A ballistic investigation[1] by this arsenal and studies by other organizations revealed that face hardened armor is preferable under some circumstances of low obliquity penetration with matching or undermatching projectiles, but general all around protection considering obliquities and overmatching projectiles, is best afforded by homogeneous armor. Add to this the increased cost of producing face hardened armor and the poor performance face hardened armor exhibited in the early tank battles in North Africa and it is seen why there was very little stress by the Ordnance Department to either use or do research on face hardened armor. It should be mentioned that N.D.R.C. was encouraged to carry on investigations of both carburized and flame hardened armor.

Face hardened armor continued to be used in aircraft protection, and early in the war, the arsenal was requested to investigate the use of low alloy steels in face hardened armor in order to conserve the 5% nickel steel being used. In this study[2], the ballistic tests as well as the metallurgical tests were conducted at the arsenal. The metallurgical examination consisted of a thorough microscopic examination of both case and core, notched and unnotched Izod impact tests, and hardness surveys across the thickness. The inferior toughness of most of the steels as heat treated in 3/8" thick plates was not satisfactorily differentiated by the impact tests, but the presence of ferrite in the core of the lower alloy steels correlated very well with their inferior shock resistance (spalling). Face spalling was correlated with excessive grain boundary carbides in the case. Two compositions (Cr-Mo-V and 3½% Ni-Cr-Mo) were found to possess satisfactory ballistic properties because of the absence of ferrite in the core structure of these plates.

The other investigations[3] of face hardened armor were conducted after the introduction of the fracture tests for toughness and steel soundness. In most of these investigations it was found that the fracture tests and notched bar impact tests reveal the ability of face hardened armor to withstand shock and penetration without spalling. Several of the investigations[4] were conducted on thin face hardened armor of the aircraft type which had been processed at Buick under N.D.R.C. and tested at the Proving Center, Aberdeen. Although

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1. Appendix A, Report No. 123.
2. Appendix A, Report No. 125.
3. Appendix A, Report Nos. 161, 171, 183, 194, 222 and 227.
4. Appendix A, Report Nos. 183, 194 and 227.

a detailed study was conducted by Buick, a few groups of plates representing the most promising face hardened armor were submitted to the arsenal for metallurgical study. The studies at the arsenal revealed that presence of bainitic structures in the core of low alloy NE type steels resulted in inferior shock resistance. A 4-5% nickel face hardened armor used for comparison exhibited satisfactory shock resistance in ballistic tests because it was possible in heat treating the latter steel to obtain a martensitic structure in the core.

Key to Code Designations of the Various Types of Reports

E - Experimental Report

SC - Subcommittee on Cast Armor Report

SR - Subcommittee on Rolled Armor Report

M - Memorandum Report

List of Armor Reports, Chronologically Arranged

1938

1. 11 July. Report No. E710/261. Correlation of Microstructure and Ballistic Properties of Armor Plate, Part I, Homogeneous Plate. E. L. Reed and S. L. Kruegel.

2. 13 October. Report No. E710/261-1. Correlation of Microstructure and Ballistic Properties of Armor Plate, Part II, Face Hardened Plate. E. L. Reed and S. L. Kruegel.

1939

3. 6 April. Report No. E710/292. Reheat Treatment of Experimental 1" Homogeneous Armor Plate. E. L. Reed and S. L. Kruegel.

1940

4. 25 March. Report No. E710/358. Memorandum Investigation of Sample of 1" Armor Plate Submitted by Capt. Haskell. E. L. Reed.

5. 15 April. Report No. E710/355. A Preliminary Study of the Ballistic Properties of Flame-Hardened Armor Plate. E. L. Reed and S. L. Kruegel.

6. 1 May. Report No. E710/356. A Comparison of the Ballistic Efficiency of Recent Face Hardened and Homogeneous Armor Plates. E. L. Reed and S. L. Kruegel.

7. 6 June. Report No. E710/357. A Study of a Forged Hot Die Steel for Use as Armor Plate Submitted by the Achorn Steel Company. E. L. Reed and S. L. Kruegel.

8. 5 July. Report No. E710/361. Examination of Sample of 1" Armor Plate Showing Surface Defect Known as "Alligator Skin". E. L. Reed.

9. 5 July. Report No. E710/360. Examination of Two 5/8" Disston Face-Hardened Armor Plates. E. L. Reed.

10. 12 July. Report No. E710/362. Examination of High Quality Experimental ½" Homogeneous Plate. E. L. Reed.

11. 21 October. Report No. E710/363. Examination of Two Experimental Cast Armor Plates Submitted by Lebanon Steel Foundry. E. L. Reed and S. L. Kruegel.

12. 1 November. Report No. E710/365. Metallurgical Examination of Large Back Spall from a 1½" Face Hardened Disston Plate. E. L. Reed.

13. 1940. Report SC No. 1. Hardness Surveys of a Flame Hardened 1½" Cast Armor Plate 18"x18". E. L. Reed.

14. 23 December. Report SR No. 1. Ballistic Tests of Low Alloy Steel Homogeneous Armor Plate. E. L. Reed.

15. 26 December. Report SC No. 2. Ballistic Tests on Cast Turret. E. L. Reed.

16. 26 December. Report SC No. 3. Ballistic Tests on Welded Cast Turret. E. L. Reed.

17. 26 December. Report SR No. 2. Examination of Punched and Drilled Holes in 1/4" Armor Plate. E. L. Reed.

1941

18. 3 January. Report SC No. 4. Special Drill for Drilling Hard Armor Plate. E. L. Reed.

19. 4 January. Report SC No. 5. Correlation of Ballistic Properties and Brinell Hardness vs. Thickness of Cast Armor Plate. S. L. Kruegel.

20. 9 January. Report SC No. 6. Ballistic Tests on Welded Turret for Medium Tank. E. L. Reed.

21. 9 January. Report SR No. 3. Ballistic Tests on Welded Turret for Medium Tank. E. L. Reed.

22. 14 January. Report SC No. 7. Ballistic Tests on Riveted Turret. E. L. Reed.

23. 14 January. Report SR No. 4. Ballistic Tests on Riveted Turret. E. L. Reed.

24. 15 January. Report SR No. 5. First Partial Report on the Development of Rolled Homogeneous Armor Plate. E. L. Reed and S. L. Kruegel.

25. 17 January. Report SC No. [illegible]. Ballistic Tests on Cast Turret. E. L. Reed.

26. 17 January. Report SR No. 6. Ballistic Tests on Cast Turret. E. L. Reed.

27. 17 January. Report SC No. 9. Ballistic Test of Cast Top Hull for Medium Tank. E. L. Reed.

28. 17 January. Report SR No. 7. Ballistic Test of Cast Top Hull for Medium Tank. E. L. Reed.

29. 27 January. Report SC No. 10. Ballistic Tests on Welded Turret. E. L. Reed.

30. 27 January. Report SR No. 9. Ballistic Tests on Welded Turret. E. L. Reed.

31. 27 January. Report SR No. 8. Correlation of Brinell Hardness and Ballistic Limits of Homogeneous Rolled Plates. E. L. Reed.

32. 18 February. Report SC No. 11. Inspection of Homogeneous Cast Armor.

33. 18 February. Report SR No. 10. Hardness Data on Homogeneous Plate. E. L. Reed.

34. 20 February. Report SR No. 11. Metallurgical Examination of Two Experimental Rolled Homogeneous Plates ½" Thick. E. L. Reed.

35. 20 February. Report SR No. 12. Metallurgical Examination of Two Rolled Face Hardened Armor Plates 5/8" Thick. E. L. Reed.

36. 26 February. Report SR No. 13. Microscopic Examination of Armor Plate Showing Surface Defect Known as "Alligator Skin". E. L. Reed.

37. 26 February. Report SR No. 14. Metallurgical Examination of Large Back Spall from 1½" Rolled and Carburized Armor Plate. E. L. Reed.

38. 7 March. Report SC No. 12. Ballistic Properties of a High Quality Flame Hardened 1" Cast Armor Plate. E. L. Reed and S. L. Kruegel.

39. 7 March. Report SR No. 15. Ballistic Properties of a High Quality Flame Hardened 1" Cast Armor Plate. E. L. Reed and S. L. Kruegel.

40. 10 March. Report SR No. 16. Examination of Face Hardened 7/8"-1-7/16" Armor Plate. E. L. Reed and S. L. Kruegel.

41. 18 March. Report SC No. 13. A Preliminary Study of the Ballistic Properties of Flame Hardened Armor Plates. E. L. Reed and S. L. Kruegel

42. 18 March. Report SR No. 17. A Preliminary Study of the Ballistic Properties of Flame Hardened Armor Plates. E. L. Reed and S. L. Kruegel

43. 21 March. Report SC No. 14. Effect of Various Deoxidizers and Homogenizing Temperatures on the Microstructure and Physical Properties of a Cast Armor Plate. E. L. Reed and S. L. Kruegel.

44. 2 April. Report No. E710/369. The Saleh Diffusion Process as Applied to Light Armor Plate. E. L. Reed and S. L. Kruegel.

45. 10 April. Report SC No. 15. Data on Machining of Armor Plate Castings. N. A. Matthews.

46. 10 April. Report SR No. 18. Data on Machining of Armor Plate Castings. N. A. Matthews.

47. 14 April. Report SC No. 16. Ballistic Tests on Welded Turret. E. L. Reed.

48. 14 April. Report SR No. 19. Ballistic Tests on Welded Turret. E. L. Reed.

49. 14 April. Report SR No. 20. Examination of 1½" Face Hardened Armor Plate. E. L. Reed and S. L. Kruegel.

50. 15 April. Report SR No. 21. Examination of a Defective Rolled and Carburized Plate 1-1/4 inches Thick. E. L. Reed and S. L. Kruegel.

51. 22 April. Report SC No. 18. Ballistic Tests on Butt Welds Joining Cast and Rolled Armor. N.A. Matthews.

52. 22 April. Report SR No. 24. Ballistic Tests on Butt Welds Joining Cast and Rolled Armor. N. A. Matthews.

53. 25 April. Report No. E710/370. "Five Point" Deephard Process Applied to Light Armor Plate. E. L. Reed and S. L. Kruegel.

54. 30 April. Report SR No. 25. Ballistic Test of Specially Heat Treated ½" Homogeneous Armor Plate. E. L. Reed and S. L. Kruegel.

55. 5 May. Report No. E710/371. Progress Report - Cold Heading Vs. Hot Heading and Rivet Design. N. A. Matthews.

56. 7 May. Report SR No. 22. Test of Laminated Thin Armor Plate. E. L. Reed and S. L. Kruegel.

57. 7 May. Report SR No. 23. Examination of 1½" Rolled and Carburized Armor Plate. E. L. Reed and S. L. Kruegel.

58. 16 May. Report No. E710/372. Metallurgical Examination of Two Defective Cast Armor Base Rings. E. L. Reed.

59. 1941. Report No. E710/373. Progress Report on Cold Heading Vs. Hot Heading and Rivet Design. N. A. Matthews.

60. 22 May. Report SC No. 19. Low Temperature Impact Testing. E. L. Reed

61. 2 June. Report SR No. 26. Tabulation of Metallurgical and Ballistic Properties of Miscellaneous Armor Steels. N. A. Matthews.

62. 4 June. Report SC No. 17. Metallurgical Examination of Two Defective Cast Armor Base Rings. E. L. Reed.

63. 5 June. Report No. E710/374. Metallurgical Examination of a Defective Cast Armor Front End Casting for Light Tank M3. E. L. Reed.

64. 11 June. Report SC No. 22. Ballistic Tests on Top Hull for Medium Tank M3 (Canadian No. 1). N. A. Matthews.

65. 12 June. Report No. E710/375. Metallurgical Examination of Two Heavy Cast Armor Plates. E. L. Reed.

66. 14 June. Report SC No. 23. Ballistic Test of Cast Armor Base Ring for Light Tank M3 Reheat Treated to Brinell Hardness of 255. N. A. Matthews

67. 17 June. Report SC No. 21. Ballistic Test of Welded Cast Armor Test Plate. N. A. Matthews.

68. 24 June. Report SC No. 20. Metallurgical Examination of Two Heavy Cast Armor Plates. E. L. Reed.

69. 30 June. Report No. E710/379. Metallurgical Examination of Rivets from Light Tank Turret M2A4 #322. H. G. Carter.

70. 10 July. Report No. E710/376. Metallurgical Examination of a Face Hardened and a Homogeneous 2" Experimental Armor Plate. E. L. Reed and S. L. Kruegel.

71. 10 July. Report SR No. 27. Metallurgical Examination of a Face Hardened and a Homogeneous 2" Experimental Armor Plate. E. L. Reed and S. L. Kruegel.

72. 18 July. Report SC No. 24. Correlation of Ballistic Properties and Chemistry in Heavy Cast Homogeneous Armor Plate. J. F. Sullivan.

73. 18 July. Report SR No. 28. Correlation of Ballistic Properties and Chemistry in Heavy Cast Homogeneous Armor Plate. J. F. Sullivan.

74. 18 July. Report SC No. 25. Ballistic Test of 75 m/m Gun Housing for M-3 Medium Tank. N. A. Matthews.

75. 18 July. Report SC No. 26. Ballistic Tests of Welded Penetration in Cast Armor. N. A. Matthews.

76. 5 August. Report No. E710/378. A Metallurgical Study of 1" Face Hardened Armor Plates Submitted by the Carnegie-Illinois Steel Corporation. E. L. Reed.

77. 14 August. Report No. E710/3[illegible]1. Metallurgical Examination and Ballistic Properties of Four Nickel Alloys. E. L. Reed.

78. 14 August. Report SR No. 30. Metallurgical Examination and Ballistic Properties of Four Nickel Alloys. E. L. Reed.

79. 16 August. Report No. E710/383. Metallurgical Examination of Armor Plate in a Light Tank Turret. E. L. Reed and N. A. Matthews.

80. 16 August. Report SR No. 32. Metallurgical Examination of the Armor Plate in a Light Tank Turret. N. A. Matthews and E. L. Reed.

81. 20 August. Report No. E710/385. Metallurgical Examination of Experimental 2" Rolled Disston Armor Plates (Carburized and Homogeneous). E. L. Reed.

82. 20 August. Report SR No. 31. Metallurgical Examination of Experimental 2" Rolled Armor Plates (Carburized and Homogeneous). E. L. Reed.

83. 26 August. Report No. E710/382. A Preliminary Study on the Heat Treatment of Chromium-Molybdenum Cast Armor Plate. E. L. Reed.

84. 26 August. Report SC No. 27. A Preliminary Study on the Heat Treatment of Chromium-Molybdenum Cast Armor Plate. E. L. Reed.

85. 29 August. Report SR No. 33. A Study of a Forged Hot Die Steel for Use as Armor Plate. E. L. Reed and S. L. Kruegel.

86. 6 September. Report No. E710/387. Metallurgical Examination of Experimental Cast Armor Turret No. 2 Manufactured by the General Steel Castings Corp. E. L. Reed and N. A. Matthews.

87. 8 September. Report SC No. 28. Metallurgical Examination of Experimental Cast Armor Turret. E. L. Reed and N. A. Matthews.

88. 9 September. Report No. E710/384. Metallographic Study of the Deformation of Homogeneous Armor Plate under Impact of Ball and Armor Piercing Projectiles. E.L. Reed and N. A. Matthews.

89. 9 September. Report SC No. 29, Metallographic Study of the Deformation of Homogeneous Armor Plate under Impact of Ball and Armor Piercing Projectiles. N. A. Matthews and E. L. Reed.

90. 9 September. Report SR No. 35. Metallographic Study of the Deformation of Homogeneous Armor Plate under Impact of Ball and Armor Piercing Projectiles. N. A. Matthews and E. L. Reed.

91. 20 October. Report SR No. 34. Correlation of Microstructure and Ballistic Properties of Armor Plate. E. L. Reed and S. L. Kruegel.

92. 29 October. Report No. E710/393. Metallurgical Examination of Punchings from Cast Turret of British A-12 Infantry Tank. E. L. Reed and N. A. Matthews.

93. 30 October. Report No. E710/394. The Application of Colmonoy No. 1 and Dymonhard No. 65 to the Surface Hardening of Armor Plate. E. L. Reed and N. A. Matthews.

94. 3 November. Report SC No. 30. Correlation of Metallurgical Properties with Ballistic Properties of Cast Armor. E. L. Reed and M. Bolotsky.

95. 3 November. Report SR No. 29. Correlation of Microstructure and Ballistic Properties of Armor Plate. E. L. Reed and S. L. Kruegel.

96. 4 November. Report No. E710/395. Metallurgical Examination of ½" Countersunk Rivets. E. L. Reed and A. Hurlich.

97. 4 November. Report SR No. 36. Ballistic Tests of Experimental One-Half Inch Low Alloy Homogeneous Armor Plate. E. L. Reed.

98. 15 November. Report No. E710/396. Experimental 1½" Low Alloy Homogeneous Rolled Armor. E. L. Reed and N. A. Matthews.

99. 15 November. Report SR No. 40. Experimental 1½" Low Alloy Homogeneous Rolled Armor. E. L. Reed and N. A. Matthews.

100. 19 November. Report SR No. 37. Reheat Treatment of Experimental 1" Homogeneous Armor Plate. E. L. Reed and S. L. Kruegel.

101. 25 November. Report SR No. 39. A Comparison of the Ballistic Efficiency of Recent Face Hardened and Homogeneous Armor Plates. E. L. Reed and S. L. Kruegel.

102. 26 November. Report SR No. 38. Experimental One-Inch Thick Armor Plate E. L. Reed.

103. 1 December. Report No. E710/392. Metallurgical Examination and Ballistic Tests of Cast Armor Plate Submitted by the General Alloys Company. E. L. Reed and A. Hurlich.

104. 7 December. Report No. E710/397. The Use of the Metallizing Process in Selective Carburizing of Armor Plate. E. L. Reed and N. A. Matthews.

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105. 13 January. Report No. E710/407. Metallurgical Examination of Two Disston 1½" Rolled Homogeneous Armor Plates. E. L. Reed and N. A. Matthews.

106. 13 January. Report No. E710/408. Metallographic Examination of 1/4" Hard Rolled Homogeneous Armor Plate. E. L. Reed and A. Hurlich.

107. 14 January. Report No. SR 41. Metallographic Examination of 1/4" Hard Rolled Homogeneous Armor Plate. E. L. Reed and A. Hurlich.

108. 11 February. Report No. E710/409. Ballistic and Metallurgical Properties of High Alloy Face Hardened Armor Plate Made by the Pluramelt Process. E. L. Reed, A. Hurlich, and M. Bolotsky.

109. 17 February. Report No. E710/412. Etching of Carbides in Steel by Means of Murakami's Reagent. E. L. Reed and A. Hurlich.

110. 17 February. Report SC No. 31. Etching of Carbides in Steel by Means of Murakami's Reagent. E. L. Reed and A. Hurlich.

111. 17 February. Report No. SR 42. Etching of Carbides in Steel by Means of Murakami's Reagent. E. L. Reed and A. Hurlich.

112. 5 March. Report SR No. 43. Manganese-Molybdenum-Silicon Steel -- Carburizing Grade. W. E. Jominy, Research Laboratories Div., General Motors Corp.

113. 25 April. Report No. E710/428. Metallurgical Data on Certain Cast Armor Test Plates Tested at A.P.G. as a Part of the Cast Armor Low Alloy Development Program. A. Hurlich, P. V. Riffin, and M. Bolotsky.

114. 25 April. Report SC No. 32. Metallurgical Data on Certain Cast Armor Test Plates Tested at A.P.G. as a Part of the Cast Armor Low Alloy Development Program. A. Hurlich, P. V. Riffin, and M. Bolotsky.

115. 6 May. Report No. E710/429. Types of Failure Occurring in the Shock Test of ½" Homogeneous Armor with Caliber .50 AP Projectiles. N. A. Matthews.

116. 6 May. Report SR No. 44. Types of Failure Occurring in the Shock Test of 1/2" Homogeneous Armor with Caliber .50 A.P. Projectiles. N. A. Matthews.

117. 13 May. Report No. E710/426. Development of Low Alloy Cast Armor Between February and May 1942. E. L. Reed and N. A. Matthews.

118. 16 May. Report SR No. 45. Metallurgical Data on 1½" Thick Rolled Homogeneous Armor Test Plates Tested at Aberdeen Proving Ground as a Part of the Rolled Armor Low Alloy Development Program. N. Bolotsky, P. V. Riffin, and A. Hurlich.

119. 4 June. Report SC No. 33. Correlation of Data on Development Low Alloy Cast Armor Test Plates Processed between February and May 1942. A. Hurlich.

120. 24 July. Report No. E710/451. Armor Plate--Further Studies of the Mechanism of Penetration of Homogeneous Armor Plate. A. Hurlich.

121. 27 July. Report No. E710/421. Cast Armor--Metallurgical Examination of a Defective 1½" Cast Armor Plate Submitted by the Symington-Gould Corp. M. Bolotsky.

122. 24 August. Report SC No. 34. Metallurgical Examination of Five Development Low Alloy Cast Plates That Failed the 75 MM.A.P. Shock Test M. Bolotsky.

123. 28 September. Report No. E710/456. Rolled Armor-Ballistic Properties of Rolled Face Hardened Armor and Rolled Homogeneous Armor of various Hardnesses at Normal Incidence and at Various Obliquities. J. F. Sullivan.

124. 7 October. Report SC No. 35. Comparison of Slug Test Shock Results on 1-1/4-2-1/4" Cast Armor under Sepcification AXS-492, Revision 2, and AXS-492, Revision 2, Amendment 1, Dated August 27, 1942. N. A. Matthews.

125. 24 November. Report No. E710/459. Armor Plate - Face Hardened--Ballistic and Metallurgical Investigation of Experimental Low Alloy Face Hardened Armor. E. L. Reed and P. V. Riffin.

126. 22 December. Report No. SC 36. Summary of Cast Armor Shock Development Tests--Specifications AXS-492, Revision 2, Amendment 1. N. A. Matthews.

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127. 14 January. Report SR No. 46. Correlation Between Ballistic Limit and True-Stress True-Strain Value in Homogeneous Armor. J. H. Hollomon.

128. 21 January. Report SC No. 37. Metallurgical Examination of 1½" and 2" Cast Armor Tested with the 75 MM T21 Slug. P. V. Riffin.

129. 16 March. Report SC No. 38. Results of Low Temperature Ballistic Tests on Cast Armor Test Plates. N. A. Matthews.

130. 19 March. Report SR No. 47. Results of Low Temperature Ballistic Tests on Rolled Homogeneous Armor Test Plates. N. A. Matthews.

131. 5 May. Report No. E710/499. Armor Plate--The Metallurgical and Ballistic Properties of 1" Cast Armor Test Plates Manufactured by Kelsey-Hayes Wheel Co. P. V. Riffin.

132. 17 May. Report No. E710/500. Armor--Metallurgical Examination of Cast Gun Shield Armor Four to Six Inches in Thickness. A. Hurlich.

133. 30 June. Report No. E710/497. Armor Plate--Cast, Ballistic and Metallurgical Investigation of SAE 1035 Experimental 1-3/4" Cast Armor. E. L. Reed.

134. 26 July. Report No. E710/533. Armor Plate--Rolled, the Inadequacy of the Unnotched Tensile Impact Test as an Indicator of the Ballistic Quality of Rolled Homogeneous Armor. E. L. Reed.

135. 28 July. Report No. E710/530. Armor--Metallurgical Investigation of the Fibre Fracture Test Used by the Union Steel Castings Division of Blaw-Knox Company. A. Hurlich.

136. 1 August. Report No. E710/532. Armor--Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels upon Quenching. A. Hurlich.

137. 16 August. Report No. E710/534. Armor Plate--Correlation of Metallurgical Properties with the Low Temperature Ballistic Shock Characteristics of 1" to 2" Low Alloy Cast Armor Tested at Camp Shilo. P. V. Riffin.

138. 3 September. Report No. E710/495. Armor--Preliminary Study of the Effect of Several Alloying Elements and Addition Agents upon the Metallurgical Properties of Manganese-Molybdenum Steel Used in Armor. P. V. Riffin.

139. 20 September. Report No. E710/258. Armor--Metallurgical Examination of Hull Bow Casting, Serial No. 134 for Medium Tank M4, Manufactured by American Steel Foundries. A. Hurlich.

140. 5 October. Report No. E710/413. Armor-- A Preliminary Study of the Effects of the Conchoidal Fracture upon the Physical and Metallurgical Characteristics of Cast Armor. A. Hurlich.

141. 5 October. Report No. M710/477. Metallurgical Examination of Defective 3" Homogeneous Rolled Armor Plate Used for Projectile Testing. N. A. Matthews.

142. 6 October. Report No. E710/414. Armor--Metallurgical Examination of Cast Turret No. 757 for M4 Tank, Manufactured by Union Steel Castings Co. Ballistically Tested at Subzero Temperatures at Camp Shilo, Canada. A. Hurlich.

143. 15 October. Report No. E710/493. Aircraft Armor--An Analysis of Firings of Rolled Homogeneous Armor Submitted under Specification ANOS-1. J. F. Sullivan.

144. 18 October. Report No. M710/587. Metallurgical Examination of Ford Motor Co. 1" Cast Armor Test Plates. N. A. Matthews.

145. 20 October. Report No. M710/547. Metallurgical Examination of Sections from Two Cast Armor Final Drive Housings. P. V. Riffin.

146. 21 October. Report No. E710/507. Armor Plate--Cast, Metallurgical Examination of Failed Bow Machine Gun Casting from Cadillac Light Tank, M5. E. L. Reed.

147. 25 October. Report No. M710/548. Metallurgical Examination of Defective Carnegie-Illinois 2-1/4", 60 mm. and 2½" Homogeneous Armor Plates. P. V. Riffin.

148. 26 October. Report No. E710/546. Armor Plate - Rolled, Ballistic and Metallurgical Properties of 1½" SAE 1035 Rolled Homogeneous Armor Plate. E. L. Reed.

149. 2 November. Report No. M710/549. Jones and Laughlin 1" Rolled Homogeneous Armor. P. V. Riffin.

150. 8 November. Report No. E710/550. Armor Plate—Cast, Ballistic and Metallurgical Investigation of Experimental 1½" Pearlite Malleablized Cast Iron. E. L. Reed.

151. 12 November. Report No. M710/554. Metallurgical Examination of Samples from "Nelson Process" 1/4", 3/8", and 1/2" Armor Plate. N. A. Matthews.

152. 16 November. Report No. M710/555. Metallurgical Examination of American Steel Foundries 1" Cast Armor Test Plates. N. A. Matthews.

153. 20 November. Report No. M710/558. Metallurgical Examination of Six 1" Rolled Homogeneous Armor Plates Manufactured by Great Lakes Steel Corporation. P. V. Riffin.

154. 4 December. Report No. M710/563. Metallurgical Examination of Side-wall Section of Cast Turret for T23 Tank Manufactured by General Steel Castings Corporation. P. V. Riffin.

155. 8 December. Report No. M710/564. Metallurgical Examination of Defective 3/16" Hard Homogeneous Armor Manufactured by American Car & Foundry Co.

156. 8 December. Report No. M710/565. Metallurgical Examination of Six 1½" Rolled Homogeneous Armor Plates Manufactured by Carnegie-Illinois Steel Corp. N. A. Matthews.

157. 10 December. Report No. M710/567. Metallurgical Examination of Twelve 1" Cast Homogeneous Armor Plates of Varying Hardnesses Manufactured by Lebanon Steel Foundry. N. A. Matthews.

158. 13 December. Report No. E710/566. Armor—Preliminary Metallurgical Studies of Experimental Face Hardened Cast and Rolled Armor. E. L. Reed.

159. 15 December. Report No. M710/570. Correlation of Metallurgical Characteristics of 1½" Homogeneous Cast Armor with Their Ballistic Properties at Temperatures of -48°F. to -72°F. A. Hurlich.

160. 27 December. Report No. E710/572. Armor—Temper Brittleness in Cast and Rolled Armor Plate. E. L. Reed.

161. 31 December. Report No. M710/574. Metallurgical Examination of Ten 1" Face Hardened Armor Plates Manufactured by American Car & Foundry Co. P. V. Riffin and M. Yoffa.

162. 6 January. Report No. M710/576. Effect of Directional Properties on Rolled Homogeneous Armor. E. L. Reed.

163. 26 January. Report No. M710/583. Metallurgical Examination of 2½" Rolled Homogeneous Armor Plate Manufactured by Henry Disston and Sons, Inc. which Backspalled under the PTP Test. A. Hurlich.

164. 27 January. Report No. M710/584. Metallurgical Examination of 3/4" Armor Plates Manufactured by Great Lakes Steel Corp. and the Standard Steel Spring Co. M. Yoffa and P. V. Riffin.

165. 28 January. Report No. M710/585. Metallurgical Examination of Nineteen 1/4" Rolled Homogeneous Armor Plates. N. A. Matthews.

166. 31 January. Report No. E710/506. Aircraft Armor—An Empirical Approach to the Efficient Design of Armor for Aircraft. J. F. Sullivan.

167. 2 February. Report No. E710/581. Armor Plate--Rolled, Correlation Between Notched Tensile Impact Properties and Static Tensile Properties Across the Gauge and Back Spalling Tendencies in Homogeneous Rolled Armor. E. L. Reed.

168. 12 February. Report No. M710/589. Preliminary Metallurgical Examination of Thirty-Two Samples of Rolled Homogeneous Armor to Be Fired During the 1943-44 Cold Test Program. J. F. Sullivan.

169. 12 February. Report No. M710/590. Preliminary Metallurgical Examination of Twelve (12) Samples of Cast Homogeneous Armor to Be Fired During the 1943-44 Cold Test Program. J. F. Sullivan.

170. 12 February. Report No. M710/591. Metallurgical Examination of Twelve 1" Cast Armor Plates Furnished by McConway-Torley Corp. N. A. Matthews.

171. 29 February. Report No. M710/593. Metallurgical Examination of Face Hardened Armor Plate. E. L. Reed.

172. 16 March. Report No. M710/594. Preliminary Metallurgical Examination of Twenty-Four Samples of Rolled Homogeneous Armor to Be Fired During the 1943-44 Cold Test Program. J. F. Sullivan.

173. 20 March. Report No. M710/601. Metallurgical Examination of Sections from Eighteen Rolled Homogeneous Armor Plates. N. A. Matthews.

174. 29 March. Report No. M710/598. Preliminary Metallurgical Examination of Six (6) Samples of Cast Homogeneous Armor to Be Fired During the 1943-44 Cold Test Program. J. F. Sullivan.

175. 31 March. Report No. M710/602. Preliminary Metallurgical Examination of Twelve (12) Samples of Rolled Homogeneous Armor to Be Fired During the 1943-44 Cold Test Program. J. F. Sullivan.

176. 5 April. Report No. M710/604. Metallurgical Examination of Fourteen 3/8" Rolled Homogeneous Armor Plates. N. A. Matthews.

177. 6 April. Report No. E710/605. Armor Plate—Cast, Metallurgical Examination of a Mn-Cr-Ni-Mo-V Steel Used for Cast Gun Shield Armor. P. V. Riffin.

178. 8 April. Report No. M710/606. Metallurgical Examination of 1/4" Thick Rolled Homogeneous Armor Plate. E. L. Reed.

179. 18 April. Report No. M710/583-1, Metallurgical Examination of 2½" Rolled Homogeneous Armor Plate Manufactured by H. Disston and Sons, Inc. Which Backspalled Under the PTP Test. A. Hurlich.

180. 26 April. Report No. M710/624. Metallurgical Examination of 4"-5" Thick Rolled Homogeneous Armor Plate. E. L. Reed.

181. 4 May. Report No. M710/627. Metallurgical Examination of Carnegie-Illinois Steel Corp. 1½" Homogeneous Armor. N. A. Matthews.

182. 9 May. Report No. M710/629. Metallurgical Examination of Twelve ½" Rolled Armor Plates Manufactured by Republic Steel Corp. M. Yoffa.

183. 13 May. Report No. M710/631. Metallurgical Examination of Experimental 3/8" Face Hardened Armor. P. V. Riffin.

184. 30 May. Report No. M710/652. Metallurgical Examination of Six 3/8" Rolled Armor Plates Manufactured by Standard Steel Spring Co. M. Yoffa.

185. 6 June. Report No. M710/644. Metallurgical Examination of Six 5/16" Rolled Armor Plates Manufactured by Standard Steel Spring Co. M. Yoffa.

186. 7 June. Report No. M710/655. Metallurgical Examination of Six 1" Rolled Homogeneous Armor Plates Manufactured by Great Lakes Steel Corp. N. A. Matthews.

187. 14 June. Report No. M710/656. Metallurgical Examination of Fourteen 5/16" Rolled Armor Plates Manufactured by Great Lakes Steel Corp. M. Yoffa.

188. 15 June. Report No. E710/662. Armor Plate—Correlation of Metallurgical Properties with Low Temperature Ballistic Performance of 1", 1½", and 2" Rolled Armor Tested at Camp Shilo, Canada. M. Bolotsky.

189. 16 June. Report No. M710/665. Metallurgical Examination of Sections from 3"-5" Thick Face Hardened Armor. P. V. Riffin.

190. 19 June. Report No. M710/664. Study of "Woody" Fractures in Rolled Armor Plate. E. L. Reed.

191. 1 July. Report No. M710/669. Metallurgical Examination of Six ½" Rolled Homogeneous Armor Plates Manufactured by Great Lakes Steel Corp. M. Yoffa.

192. 4 July. Report No. M710/671. Metallurgical Examination of Two 1/4 Inch, Two 3/8 Inch, and Twenty-One 1/2 Inch Rolled Homogeneous Armor Plates, Manufactured by Great Lakes Steel Corp. M. Yoffa.

193. 14 July. Report No. M710/676. Metallurgical Examination of Sections from Two 4" Thick Cast Armor Plates Manufactured by Continental Foundry and Machine Company. N. A. Matthews.

194. 15 July. Report No. M710/677. Metallurgical Examination of Experimental 3/8" Face Hardened Armor. B. Phelps and P. V. Riffin.

195. 17 July. Report No. M710/675. Metallurgical Examination of Twelve 3/4" Rolled Homogeneous Armor Plates Manufactured by Carnegie-Illinois Steel Corp. M. Yoffa.

196. 21 July. Report No. M710/681. Metallurgical Examination of Section from 6" Experimental M4A3E2 Assault Turret Manufactured by Union Steel Castings Div. of Blaw-Knox Co. P. V. Riffin.

197. 24 July. Report No. E710/611. Armor Plate--Rolled, Investigation of Experimental Heat Treatments of 3/8 Inch Thick Homogeneous Armor Plate. E. L. Reed.

198. 29 July. Report No. M710/684. Metallurgical Examination of Thirteen 1/2" Rolled Homogeneous Armor Plates Manufactured by Great Lakes Steel Corp. M. Yoffa.

199. 21 August. Report No. M710/552. Charpy V-Notch Impact Properties of Rolled Homogeneous Armor Produced by Standard Steel Spring Co. N. A. Matthews.

200. 22 August. Report No. M710/690. Metallurgical Examination of 2" Cast Armor Manufactured by Continental Foundry and Machine Co. P. V. Riffin and N. A. Matthews.

201. 28 August. Report No. M710/520. Heavy Tank T26E1--Metallurgical Examination of Components Which Failed Under Ballistic Tests. P. V. Riffin.

202. 29 August. Report No. M710/257. Metallurgical Examination of Twenty-Five 1½ Inch Rolled Homogeneous Armor Plates Manufactured by Republic Steel Corporation. M. Yoffa.

203. 30 August. Report No. M710/691. Metallurgical Examination of Samples of 2-1/4" Thick Rolled Homogeneous Armor Manufactured by Carnegie-Illinois Steel Corporation. E. L. Reed.

204. 31 August. Report No. M710/695. Metallurgical Examination of 10" Cast Homogeneous Armor Manufactured by General Steel Castings Corp. and 6" Cast Homogeneous Armor Manufactured by Union Steel Castings Co., Heats 8630 and 1242B Respectively. A. Hurlich.

205. 1 September. Report No. E710/678. Armor--Cast, The Development of Combinations of Compositions and Heat Treatments to Yield Optimum Shock Properties in Cast Armor 1 to 6 Inches Thick. H. H. Zornig, N. A. Matthews, J. H. Hollomon, A. Hurlich, L. D. Jaffe, M. Norton.

206. 12 September. Report No. M710/694. Metallurgical Examination of Twenty 1 Inch Rolled Homogeneous Armor Plates Manufactured by Standard Steel Spring Co. M. Yoffa.

207. 27 September. Report No. M710/698. Preliminary Metallurgical Examination of Twenty-Four (24) Samples of 1½" Cast Homogeneous Armor to Be Fired During the 1943-44 Cold Test Program. B. Phelps and J. F. Sullivan.

208 25 October. Report No. M710/285. Metallurgical Examination of Twelve 4 Inch Rolled Homogeneous Armor Plates Manufactured by Gary Armor Plate Plant. M. Yoffa and E. L. Reed.

209. 28 October. Report No. M710/321. Metallurgical Examination of Two 1/4" Rolled Homogeneous Armor Plates Which Exhibited Differences in Steel Soundness Under Ballistic Tests. P. V. Riffin.

210. 14 November. Report No. M710/344. Metallurgical Examination of Fourteen 3/4-Inch Rolled Homogeneous Armor Plates Manufactured by Great Lakes Steel Corp. M. Yoffa.

211. 15 November. Report No. M710/345. Metallurgical Examination of Samples from the T16 Universal Carrier Hull. B. Phelps.

212. 27 November. Report No. E710/688. Armor--Cast, The Development of Chemical Compositions for 4½" Cast Armor Satisfying the Requirements of the Fibre Fracture Test after Heat Treatment. P. V. Riffin.

213. 28 November. Report No. M710/347. Metallurgical Examination of Two T23 Cast Turrets Produced by the Continental Foundry and Machine Co. A. Hurlich.

214. 8 December. Report No. M710/560. Metallurgical Examination of 4"-6" Thick Cast Armor. M. Yoffa and E. L. Reed.

215. 15 December. Report No. M710/561. Metallurgical Examination of 4"-6" Thick Cast Armor. M. Yoffa and E. L. Reed.

216. 15 December. Report No. M710/562. Metallurgical Examination of Two 105 MM Gun Shields Serial No. 1 and Serial No. 2, Heat No. 1506 Manufactured by Continental Foundry & Machine Co. P. V. Riffin.

217. 16 December. Report No. M710/703. Metallurgical Examination of Sample from Cast Hull Front Section E9049, Serial No. 32. B. Phelps.

218. 22 December. Report No. M710/705. Metallurgical Examination of 2" Cast Armor Shock Tested with 105 MM. Proof Projectiles. M. Yoffa and E. L. Reed.

219. 29 December. Report No. M710/707. Metallurgical Examination of Two 4" Sections of Cast Armor Manufactured by Pittsburgh Steel Foundry. B. Phelps.

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220. 2 January. Report No. M710/714. Metallurgical Examination of a Cast Armor Gun Shield Manufactured by General Steel Castings Corp. M. Yoffa.

221. 17 January. Report SR No. 48. Study of "Woody" Fractures in Rolled Armor Plate. E. L. Reed.

222. 19 January. Report No. M710/716. Metallurgical Examination of Twelve $2\frac{1}{2}$" Thick Rolled Homogeneous and Sixteen $2\frac{1}{2}$" Thick Face Hardened Armor Plates Manufactured by Carnegie-Illinois Steel Corp. M. Yoffa and E. L. Reed.

223. 6 February. Report No. M710/719. Metallurgical Examination of Cast Hull (Front Section) Manufactured by General Steel Castings Corp. B. Phelps.

224. 12 February. Report No. M710/721. Metallurgical Examination of Flame Hardened Gun Shield Manufactured by Continental Foundry and Machine Co. M. Yoffa.

225. 13 February. Report No. M710/222. Metallurgical Examination of 4" Thick Cast Armor. M. Yoffa.

226. 16 February. Report No. M710/723. Metallurgical Examination of Eighteen Pieces of 25/64" Thick Rolled Homogeneous Armor. M. Yoffa.

227. 1 March. Report No. M710/726. Metallurgical Examination of Buick Face Hardened Armor Plate. P. V. Riffin.

228. 12 March. Report No. M710/728. Metallurgical Examination of 4" Cast Armor--Project AW-10. B. Phelps and Dr. E. L. Reed.

229. 14 March. Report No. M710/729. Metallurgical Examination of 2" Cast Armor and $2\frac{1}{2}$" Rolled Homogeneous Armor Shock Tested with 105 mm. T8 Proof Projectiles. M. Yoffa.

230. 16 March. Report No. M710/730. Metallurgical Examination of $2\frac{1}{2}$" Thick Rolled Homogeneous Armor Shock Tested with 105 mm. T8 Proof Projectile and 3" APC M62 Projectile. M. Yoffa.

231. 21 March. Report No. M710/731. Metallurgical Evaluation of a Method of Anti-Personnel Defense for the Medium Tank M4A1. A. Hurlich.

232. 28 March. Report No. M710/735. Metallurgical Examination of a Cast Turret Manufactured by the American Steel Foundries. B. Phelps.

233. 12 June. Report No. M710/753. Metallurgical Examination of a Cast Armor Turret T23 Produced by Ordnance Steel Foundry. P. V. Riffin.

234. 19 June. Report No. M710/758. Metallurgical Examination of T26E2 Cast Armor Turret No. 376 Manufactured by General Steel Castings Corp. P. V. Riffin.

235. 19 June. Report No. M710/759. The Heat Treatment of an Experimental Steel Designed to Produce 8" Thick Cast Armor of Acceptable Shock Properties. A. Hurlich.

236. 25 June. Report No. M710/762. Metallurgical Examination of 2½" to 6" Rolled Homogeneous Armor Manufactured by Great Lakes Steel Corp. and Heat Treated by Standard Steel Spring Co. M. Bolotsky.

237. 26 June. Report No. M762/320. Considerations Preliminary to the Development of Improved PTP Test Projectiles. J. F. Sullivan.

238. 28 June. Report No. M710/760. Metallurgical Examination of 1" and 2" Thick Cast Armor Used for the Development of 57 mm. and 105 mm. Proof Projectile Shock Tests. M. Yoffa and A. Hurlich.

239. 16 July. Report No. M710/765. Experimental 3" Thick Cast Armor Program Heat Treatment of Fracture Blocks from Heats Nos. 1903, 1917, 1968, and 2244, Produced by Continental Foundry & Machine Co. A. Hurlich.