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WATERTOWN ARSENAL LABORATORY

EXPERIMENTAL REPORT

NO. WAL 710/6[illegible]

ARMOR PLATE

[illegible] of Metallurgical Properties [illegible] Ballistic Performance of [illegible] Shilo, Canada

BY
[illegible]
Asst. Metallurgist

DATE 15 June 194[illegible]

WATERTOWN ARSENAL
WATERTOWN, MASS.

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Watertown Arsenal Laboratory
Report No. WAL 710/662
Problem No. B-4.11

June 15, 1944

ARMOR PLATE

Correlation of Metallurgical Properties with Low Temperature Ballistic Performance of 1", 1½", and 2" Rolled Armor Tested at Camp Shilo, Canada

OBJECT

To correlate metallurgical properties of 1", 1½", and 2" rolled homogeneous armor and 1" rolled face-hardened (carburized) armor with ballistic performance (shock and projectile-through-the plate tests) at low temperatures (-15°F. to -35°F.) in order to establish the characteristics which must be possessed by such armor for successful performance at subnormal temperatures.

CONCLUSIONS

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.

(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.

3. Examination of the 1" face-hardened (carburized) plate indicates the following remarks in regard to the whole series:

a. Shock Test

The plate that was shock tested passed the mild test applied (a 37mm M51 APC projectile at 25° obliquity at 1262 f/s) although the core hardness, judged from that of the plate examined (which was not shock tested), was 400 Brinell.

b. Projectile-Through-the Plate Test

Spalling occurred in the case of every plate of the series. The spalling behavior of the plates was due to the excessive (400 Brinell) core hardness.

4. The shock test given to the 2" plates at Camp Shilo (a 75mm slug at normal obliquity at 1500 f/s) was inadequate for separating plates possessed of good shock properties from those characterized by borderline and even poor impact strength at high rates of strain.

5. The projectile-through-the plate test given to the $1\frac{1}{2}$" and 2" plates at Camp Shilo (a 37 mm M51 APC projectile at normal obliquity) was inadequate for revealing the spalling tendencies of armor characterized by poor steel soundness.

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.

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APPROVED: H. H. Zornig

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INTRODUCTION

This report covers the metallurgical investigation conducted on samples taken from 1", $1\frac{1}{2}$", and 2" rolled homogeneous plates and a 1" rolled face hardened plate which had been subjected to ballistic tests during the period January-February 1943, at the Ordnance Proving Center Winter Detachment, located at Camp Shilo, Manitoba, Canada.

A series of plates was furnished by each manufacturer for each gauge. Each series consisted of plates from the same heat, similarly heat treated, and usually numbering five.

Prior to the firing program, tests were made to determine the lag between plate and atmosphere temperature. From these data the actual temperature of a plate during the impact of each round was determined. Plate temperatures during the period of ballistic firing varied approximately from -15°F. to -35°F.

Testing was conducted in strict conformity with the requirements of the applicable specification (AXS-495, Revision 1 or AXS-488 or AXS-490). In one instance, however, it was found that a $1\frac{1}{2}$" plate series could not withstand the slug shock test, and reversion was made to the less severe and now obsolete 75 mm AP projectile shock test at 25° obliquity in order to further classify this material. Firing was confined to the shock and projectile-through-the plate tests, since early in the program it had been determined that resistance to penetration was not affected appreciably by low temperature.

A preliminary report[1] has been written at this Arsenal in which the test results were summarized and interpreted. Based upon the ballistic tests, the metallurgical data supplied on the data sheets of the plates, and a knowledge of the past performance of the material produced by the various manufacturers, the following outstanding requirements for successful low temperature ballistic performance were stated:

1. In order to pass the specified low temperature shock requirements, armor must possess sufficient hardenability to harden throughout upon quenching without the rejection of an appreciable amount of ferrite.

2. Armor which is expected to withstand the projectile-through-plate test at low temperatures must be fabricated from cleaner steel than that now tolerated by the same test conducted at normal temperature.

During the period following the low temperature firing program, two fracture tests were developed at this Arsenal as inspection controls to be applied before ballistic testing. One, the Fracture Test for Steel Soundness, was formulated jointly with industry to control the degree of cleanliness of rolled armor at the steel source, prior to heat treatment; and the other, the Fibre Fracture Test,[2] was developed to control the quenching practice

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1. Rolled Armor Subcommittee Report No. 47 - "Results of Low Temperature Ballistic Tests on Rolled Homogeneous Armor Plates" - 19 March 1943.
2. Watertown Arsenal Laboratory Report No. 710/532 - "Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels upon Quenching" - 1 August 1943.

(and minimum hardenability) of cast and rolled armor at the heat treating facility. Both fracture tests are now incorporated in the revised specification for rolled homogeneous armor, AXS-488 (Rev. 2).

It is intended in this report to evaluate the metallurgical properties of the armor samples received by means of the two fracture and other tests, to determine the causes of failure in every case if possible, and by comparison of the ballistic results with the metallurgical data of the passing and failing plates to establish the characteristics which must be possessed by rolled armor, 1" to 2" in thickness, for successful ballistic performance at subnormal temperatures.

MATERIALS AND TEST PROCEDURE

Armor Samples Examined

Seventeen sections, approximately 8"x12"x thickness, that had been flame cut from representative good and poor rolled armor were received for examination. Sections were removed from the centers of the plates adjacent to impacts. The product of seven heat treating facilities, these comprised samples from three 1" homogeneous plates, one 1" face-hardened (carburized) plate, nine 1½" homogeneous plates, and four 2" homogeneous plates. The plates are listed in Table I with pertinent data abstracted from the corresponding Aberdeen Proving Ground Canadian Cold Test firing records. Plates are grouped by plate thickness and tabulated within thickness groups according to inferiority of ballistic performance.

A. Chemical Analysis

The chemical compositions of the seventeen plates were determined at this Arsenal in order to check the analyses reported on the C.A.S. forms.

B. Hardness Tests

Brinell hardness determinations were made on cross sections cut from the homogeneous plate samples. Brinell impressions were located 1/4" from the plate surface, midway between surface and center, and at the center of each cross-section.

A Vickers hardness survey was made on the cross section of the 1" carburized plate, across the face-hardened zone, to determine case depth. Brinell readings were taken on the case face, on the core face, and at the center of the cross section of this plate.

C. Fracture Test for Steel Soundness

Specimens 8" x 3" x T were cut in both directions for the steel soundness test. Bars were nicked with an abrasive cut off wheel for a depth of 1/8" at the midpoint of and perpendicular to the 8" direction, at both sides, and broken slowly under a forge press. Fractures were then rated for steel soundness. The same fractures were also examined and rated in accordance with the fibre fracture test for later comparison with fractures produced by a sharp blow, as specified for this test.

D. Fibre Fracture Test

Because of limited material, half of a previously broken steel quality fracture test bar was utilized to conduct the fibre fracture test of each plate. Notching was done as before except that depth of notch at each side was made equal to one quarter of the bar width. Specimens were fractured by the quick impact of a forge hammer.

E. V-Notch Charpy Impact Test

Ten standard V-notch Charpy specimens were machined from the center of each plate. In addition ten specimens were secured from each of the $1\frac{1}{2}$" and 2" plates at the region adjacent to the center specimens. These Charpy bars were located exactly midway between plate face and center in the case of the 2" plates and approximately so in the $1\frac{1}{2}$" plates. Of the ten Charpy specimens from each location, eight were taken with the long axis in the transverse direction and the notch in the longitudinal direction, and two were machined with the long axis in the longitudinal direction and the notch in the transverse direction.

To minimize scattering of results caused by variance in notch contour and surface, the roots of all notches were polished with a short piece of revolving piano wire (.01" radius) charged with alumina abrasive. After approximately one minute of polishing, contours were inspected for trueness of shape and freedom from milling cutter marks.

The transverse Charpy bars were broken in duplicate at four temperatures: 20°C., -10°C., -40°C., and -70°C. Longitudinal specimens were broken at only 20°C. The low temperatures were achieved by immersing the impact bars in an acetone-dry ice bath for a minimum of fifteen minutes at testing temperature prior to breaking.

F. Macroscopic Examination

Specimens approximately 3" long were cut in both the longitudinal and transverse direction for macroetching. Macroetched structures were examined for correlation with the respective steel soundness fractures and then photographed.

G. Microscopic Determination of Nonmetallic Inclusions

To further correlate steel quality fractures with inclusion content, microspecimens were taken across the plate thickness in both directions. The polished microspecimens were examined for amount and distribution of nonmetallic stringers, and typical conditions were photographed.

H. Hardenability

Standard Jominy bars, 3" long and 1" in diameter, were used to determine hardenability. Bars were secured in duplicate from the exact centers of the plates and usually in the transverse direction (to overcome the effects of banding). The bars were austenitized in a slightly carburizing atmosphere according to the time intervals and temperatures used by the manufacturer and then quenched in a standard fixture. Rockwell "C" hardness surveys were made on the bars on ground flats at locations corresponding to the centers of the plate sections. (.050" was ground off to insure eliminating the effects of decarburization.) One bar of each plate was also polished and etched at one flat for examination of the variation in microstructure from quenched end to air cooled end and correlation of hardness with microstructure.

I. Metallographic Examination

Metallographic examinations were made of the microspecimens previously studied for inclusion content. Photomicrographs were taken of the typical structures at the centers of all the plates except one and also, in the case of the $1\frac{1}{2}$" and 2" plates, at the area midway between center and plate face whenever the microstructure at the center was found to vary from the microstructure at this location.

RESULTS AND DISCUSSION

On individual data sheets comprising Inclosure A are listed, for each of the seventeen plates studied, the chemical analysis, heat treatment, and physical properties reported by the manufacturer, the ballistic test results, and the data secured from the various tests conducted by this laboratory. Accompanying each data sheet is a page containing photomicrographs of the microstructure and a graphical representation of the V-notch Charpy test data of the plate. Data sheets are grouped by plate thickness and arranged within each thickness group in order of armor inferiority under ballistic test, plates failing the shock test being listed first, plates failing the projectile-through-plate test following, and those passing both tests being included last.

At the end of this report, in Appendix B, on three sheets, are the complete test results and reported metallurgical data of all 1", $1\frac{1}{2}$", and 2" homogeneous rolled plates tested at Camp Shilo, the same information that was included in the appendix of the preliminary report[3] written at this Arsenal after the completion of the Shilo cold test rolled plate program. These tabulations are included in order that the metallurgical investigation of the samples examined may be correlated with the entire program.

1. Chemical Analysis

Inspection of the chemical analyses listed in the data sheets of Inclosure A reveals that chemical compositions determined at this Arsenal differed appreciably from those reported for the Van Dorn 1" plate and the Jones and Laughlin $1\frac{1}{2}$" plate. Nickel, chromium, and molybdenum contents were found to be substantially lower than reported by Van Dorn. Boron, not recorded by Jones and Laughlin, was detected in their material to the extent of .0009%. In both instances the Watertown Arsenal analysis checked with the hardenability of the plate, which was otherwise unexplainable on the basis of the manufacturer's analysis. Except for the reporting of lower carbon than was found in the Van Dorn $1\frac{1}{2}$" plate, all other manufacturers' analyses checked very well with the Watertown Arsenal determinations.

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3. See footnote 1, page 3.

The analyses of the plates tested at Shilo are typical of the compositions in use at the time the material was procured. At that period similar plates made by the same companies were regularly passing the shock and projectile-through-plate tests conducted at normal temperature.

From the data sheets in Appendix B, however, it is seen that a large number of shock failures occurred among plates of two type compositions, the Great Lakes Si-Cr-Mo-Zr analysis and the Disston high Ni-Mo composition, especially in the $1\frac{1}{2}$" gauge. It will be demonstrated in later sections of this report that the fundamental cause of this poor shock performance is the low hardenability possessed by each of these compositions, and that superiority of one type analysis over another for manufacture of 1" to 2" rolled armor is dependent primarily upon the hardenability of the steel.

Since the cold test program, the Disston Company has changed to a Ni-Cr-Mo chemistry of improved hardenability, and the Great Lakes Company has sought increased hardenability first by the addition of boron to their standard Si-Cr-Mo-Zr analysis and secondly by the accurate control of the percentages of the alloying elements necessary to achieve satisfactory hardenability for any particular thickness. Increased manganese and/or the introduction of boron has also occurred in the Ni-Cr-Mo analyses of the other armor manufacturers to compensate for reduction of molybdenum that has been necessitated at times because of shortages in the supply of this element available for rolled armor production.

2. Hardness Tests

Results of the Brinell hardness determinations are tabulated in Table II. In this table are likewise listed, for convenient comparison, the steel soundness fracture test ratings, the fibre fracture test ratings, the V-notch Charpy impact data, and the ballistic data of the plates investigated.

Comparison in Table II of Brinells taken adjacent to the surfaces of the cross sections with corresponding hardness impressions taken at the centers reveals that many plates were not fully hardened throughout upon quenching. Further comparison of hardness distribution with ballistic shock performance, moreover, indicates a correlation between incomplete hardening, as shown by drop in hardness from surface to center, and failure under shock. A more accurate and complete picture of incomplete quench hardening as the cause of shock failure will later be obtained from the data of the fibre and Charpy impact tests and from microstructure.

The hardnesses of two of the 1" plates, Carnegie-Illinois plate number 4-2-T-4 (Brinell: 352 one face, 321 other face) and American Car plate number 1702-7 (Brinell 401) are on the high side for optimum shock resistance at low temperatures. Although the 37 mm M51 APC projectile fired at 25° obliquity does not constitute a severe shock test, the behavior of the Carnegie-Illinois series was only borderline. Two of the four plates of the series, including the subject plate, although passing the test, did exhibit cracking; whereas a third companion plate failed at -27°F. by back spalling. The ballistic results for this series may have been influenced to some extent by the presence of some non-martensitic austenite decomposition products, but in view of the fibre and V-notch Charpy test results, high and non-uniform hardness are considered the predominant factors. All of these factors will be discussed in more detail in later sections of the report.

Subsequent to the Shilo program the severity of the shock test for evaluating 1" homogeneous plate was increased by the substitution of a 75 mm Slug projectile at normal obliquity for the 37 mm APC M51 25° obliquity round. In the recent version of specification AXS-488 (Rev. 2) this change has been made mandatory.

Only one of the three plates comprising the American Car series was subjected to ballistic shock. Tested at -15°F., this companion plate to the one examined did not crack upon being impacted at 25° obliquity with the 37 mm APC M51 projectile. While judged satisfactory by this criterion, the hardness of this series is too high for the armor to be able to withstand a severe shock test. However, since this type of armor was designed for maximum resistance to penetration by matching or undermatching projectiles, shock resistance is a secondary consideration.

Hardnesses of the other two 1" plates are considered satisfactory for shock resistance. That of the Van Dorn plate, 255/269 Brinell, is on the low side, as a result of which the plate failed to meet the resistance to penetration requirements.

It is well known that the armor plate characteristics in 1" to 2" rolled armor that are mainly responsible for plate spalling revealed by the projectile-through-the plate test are high hardness and/or excessive laminations in the steel. Since metallurgical tests indicated that both the Carnegie-Illinois and American Car 1" plates had been fabricated from clean steel, the failure of the former plate and the tendency to spall of the American Car plate 1702-7 and its two companion plates (See Data Sheets No. 3 and 4, Inclosure A) are attributed solely to the high hardness levels of the plates.

The effect of low temperature in reducing the hardness level permissible in 1" plate subjected to the projectile-through-the plate test is illustrated by the Carnegie series, wherein spalling did not occur until testing temperature had been lowered from -18°F. to -27°F. In Table III is shown the increase in spalling within several series, including the Carnegie 1" plate series, resulting from the lowering of the projectile-through-the plate testing temperature. The table includes spalling due to either poor steel quality or high hardness.

It should be noted that the critical temperature range at which spalling first occurred in all of the series listed in Table III is approximately -25°F. to -30°F. The same phenomenon and same critical temperature range have been detected by the British in carefully controlled experiments with $1\frac{1}{2}$" plates. In their experiments apparently hardness alone was the cause of spalling at the testing temperatures involved.

Among the heavier gauge plates, except for the Carnegie-Illinois $1\frac{1}{2}$" and 2" plates, Brinell hardness is well under the upper limit at which cracking or spalling could be expected to result from the shock or projectile-through-the plate tests because of high hardness. The Carnegie-Illinois plates will be discussed in the next two sections of this report.

Total case depth of the American Car and Foundry 1" carburized plate was revealed by the Vickers survey to be .3". This hardness survey checks the fracture and macroetch tests and verifies that the Charpy specimens machined from the center of the plate did not include part of the case.

3. Fracture Test for Steel Soundness

Following an extensive research program in cooperation with industry, a fracture test capable of being applied by inspectors at the steel source to rate and control the cleanliness of rolled armor plate was developed during the past recent months at this Arsenal. Fracture standards were formulated to classify rolled plate in accordance with continuity and number of laminations (caused by nonmetallic inclusions or ruptures occurring during processing) revealed upon fracturing a quenched and drawn sample of specified size. The dividing line between steel of acceptable quality and rejectable quality was based to a great extent upon months of correlation between fracture classifications and ballistic results of projectile-through-the plate tests.

This steel soundness fracture test is now a part of specification AXS-488 (Rev. 2), which applies to machinable rolled homogeneous armor plate in thicknesses from 1/8" to 4", inclusive, and to hard homogeneous rolled armor plate in thicknesses from 3/16" to 7/16", inclusive.

The "word standards" for the interpretation of the fracture test for steel soundness, incorporated in Appendix I of specification AXS-488 (Rev. 2), have been included in this report as Appendix A. It should be noted that armor in gauges up to and including 1-1/8" is judged rejectable when the fracture is classified as "D" or "E", whereas plate 1-1/4" to 4" in thickness is not considered rejectable until the very inferior "E" classification is encountered.

During the period when ballistic performance was being correlated with fracture classification in order to establish satisfactory or rejectable criteria, all three gauges of plate investigated in this report were tested with the same caliber projectile, the 37 mm M51 APC shot. Thus, in the case of 1" plate the projectile was overmatching, whereas only a matching condition existed against 1½" plate, and in the case of 2" plate, the projectile was undermatching. It is well known that an overmatching projectile is more likely to cause a plate of poor steel quality to spall than a matching or undermatching projectile. The severity of test, therefore, decreased with increase of plate thickness, and it would be expected, as was found during the correlation period, that the heavier the gauge, the more unsound a plate could be and still pass the projectile-through-the plate test.

Although the effect of the projectile diameter-plate thickness relationship upon tendency to spall is not recognized in the fracture standards by the setting of "D" as a passable classification for 1½" and 2" plate, the non-uniformity and inadequacy of the projectile-through-the plate test itself have been overcome in the recent revision of specifications AXS-495 (Rev. 2) and AXS-488 (Rev. 1) as specification AXS-488 (Rev. 2), which merges and revises the two specifications and requires overmatching projectiles at normal obliquity through 1½" and 2" plate (57 mm AP M70 and 75 mm AP M72, respectively) as well as for 1" plate (37 mm AP M74).

Reference should now be made to Table II, wherein are tabulated the steel soundness ratings judged from fractures broken both parallel and transverse to the final rolling direction. According to the specification, a fracture need be broken only parallel to the final rolling direction of a slab in rating steel quality. Table II indicates, as have other instances noted at this Arsenal, that fractures in both directions are preferable.

The directional characteristics of the plates, determined from the steel soundness fractures and macroetched sections, are included in Table II following the soundness fracture test ratings. These data will be discussed further in Section 6, "Macroscopic Examination".

In assigning fracture ratings to plates during the discussion to follow below, the more severe of the two classifications determined for each plate will be selected. This is permissible especially if the selected rating is that of the transverse fracture, for this fracture is in fact more representative of a plate than the longitudinal fracture, since the former constitutes a summation of many inclusion plates or planes, whereas the latter may in the case of straightaway or essentially straightaway rolled steel represent only one plane. In all instances except one where longitudinal and transverse fracture ratings of a plate differ in Table II, the transverse is seen to be the inferior fracture.

Due to the necessity for utilizing the fracture sections for other physical tests, the fracture bars having Brinells above 300 were not tempered to this hardness before fracturing, as required by the specification. However, only two plates had hardnesses significantly above 300 Brinell, the Carnegie-Illinois and the American Car and Foundry 1" plates, and other tests corroborated their steel quality fracture test ratings.

In this section the discussion will be confined to reconciling steel soundness ratings with projectile-through-the plate spalling. The effect of steel quality upon shock will be described in Section 4, "Fibre Fracture Test". Individual plates will be considered in conjunction with the ballistic results of the whole series, with the assumption made that the fracture ratings of all plates in a series are the same as that of the plate examined. No statistical tabulation can be made, however, of PTP behavior at low temperature versus steel soundness as revealed by the fracture test because the data are both insufficient and complicated by the presence of varying factors such as hardness and incomplete quench hardening.

Among the 1" plates spalling occurred in two series designated as of "C" quality. In one case (Van Dorn Plate No. 1 - Brinell 269/255) the same plate previously found acceptable and without back spalling at -16°F. spalled excessively when tested again at -34°F. In the second instance (Disston Plate No. 1 - Brinell 316/302) spalling did not occur in the series until the testing temperature had been lowered from -22°F. to -30°F. The data for both series are included in Table III. When it is remembered that similar plates manufactured by the same facilities were usually passing the same PTP test at normal temperature, these examples indicate that plate expected to consistently behave satisfactorily at low temperature when tested with overmatching projectiles at normal obliquity must be of better steel quality than that tolerated at room temperature. (Note: The Disston results may have been influenced by the hardness level as well as the steel soundness.)

It may be argued that steel quality of every plate in a series is not necessarily similar and therefore the conclusion above is not necessarily valid in regard to the Disston series. This is indeed possible, for nonmetallic content can vary from ingot to ingot within a heat and from location to location within the same ingot. Among the three series, however, whereby two companion plates were examined from each series, steel quality was found to be similar for each pair of plates. (Disston and Great Lakes $1\frac{1}{2}$" plates and Great Lakes 2" plates.) And it would be an unusual coincidence if in all the series listed in Table III the plate tested at the lowest temperature of a series, the plate that spalled, should differ in cleanliness from the companion plates which were tested at higher temperatures and did not spall.

Of the four series in the $1\frac{1}{2}$" thickness range characterized by "D" fractures, spalling occurred in two, the Carnegie-Illinois and Republic groups. A Brinell of 311/285, which approaches the upper hardness limit for satisfactory room temperature PTP penetrations, probably contributed toward the occurrence in the Carnegie-Illinois series of back spalls (borderline acceptable) at all testing temperatures from -24°F. to -35°F. In the case of the Republic plates (Brinell 245-220) spalling tendency was not revealed until temperature had been decreased from -24°F. to -33°F. The data for this series, shown in Table III, corroborate the conclusion drawn previously in regard to the quality of steel necessary for consistent satisfactory ballistic performance at subnormal temperatures.

Considering that $1\frac{1}{2}$" plates fabricated from "D" quality steel (Youngstown and Van Dorn) and even "E" quality steel (Great Lakes) did not spall at any testing temperature when penetrated with 37 mm AP projectiles (See Data sheets in Inclosure A), and recalling the discussion at the outset of this section on the effect of the projectile diameter-plate thickness relationship upon the revelation of spalling tendencies due to inclusion laminations in plate of normal hardness, it is proper to state that the PTP test given to the $1\frac{1}{2}$" plates at Camp Shilo was inadequate. Had the 57 mm AP projectile been used, there would undoubtedly have resulted a much larger percentage of failures of "D" and "E" quality material and therefore a much better correlation between steel soundness and PTP results.

Among the 2" plates, severe spalling occurred in the series characterized by "E" fractures (Great Lakes - Brinells 281/238 and 285/238) and in the series found to be of "B" steel quality (Carnegie-Illinois - Brinell 302/297). The fractures of the two Great Lakes plates examined contained many more than the minimum number of laminations required for the "E" classification. From experience with armor of similar quality, it appears probable that these plates would have failed if penetrated with the under-matching 37 mm APC M51 projectile at room temperature.

The data for the Carnegie-Illinois series are included in Table III. Again the detrimental effect of decrease in temperature is illustrated. Since steel quality of the Carnegie-Illinois sample examined was found to be excellent, it would appear that a Brinell hardness of 300 in 2" plate is excessive for resisting spalling when penetrated completely with the under-matching 37 mm APC M51 projectile at -29°F.

None of the three Ford 2" plates ("D" fracture rating and 265 Brinell) spalled at the testing temperatures, -25°F. and -26°F. This series is an indication that the conclusions in regard to the inadequacy of the PTP test for $1\frac{1}{2}$" plates expressed previously pertain to the 2" plates also.

4. Fibre Fracture Test

The fibre fracture test is the second fracture test developed at this Arsenal[4] and incorporated into specification AXS-486 (Rev. 2) to eliminate unsuitable armor prior to ballistic testing. In this test the response to quenching and resulting impact toughness of regular quenched and drawn production plates are determined by Ordnance inspectors at the heat treating facility from the appearance of the fracture produced by breaking a notched sample of specified size with a quick blow at room temperature.

Metallurgical investigations[5,6] have revealed the following information about each of the three types of fractures encountered:

a. The fibrous[7] fracture is characteristic of armor which possesses relatively high impact strength at high rates of strain. Armor which has been completely quench hardened and tempered to a hardness below approximately 340-360 Brinell (and which is free of temper brittleness) gives a fibrous fracture. Armor which contains high and/or intermediate temperature transformation products will also break with a fibrous fracture providing the hardness is sufficiently low. Generally, the higher the hardness of a "fibrous" plate, the less the quantity of non-martensitic products that it may be expected to contain. For example, in

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4. See footnote 2, page 3.
5. See footnote 2, page 3.
6. Investigations conducted subsequent to Reference No. 5 and not written up into a formal report.
7. The following are the definitions of fibrous, crystalline, and mixed fractures used at this Arsenal (Taken from Reference No. 5):

Fibrous Fracture

The fibrous fracture is characterized by a non-reflecting dark gray, rough and pitted surface. The sides of the fracture show the necking-in associated with ductile behavior.

Crystalline Fracture

The crystalline fracture is characterized by a bright silvery sheen caused by reflections from facets. The surface of the fracture tends to be flat and the sides undeformed. The fracture appears brittle in nature.

Mixed Fracture

The mixed fracture contains elements of both the fibrous and crystalline types of fractures. The crystalline region usually consists of patches or streaks in a fibrous matrix.

the case of 1" to 2" rolled plates having hardnesses below approximately 250 Brinell, fibrous fractures have been achieved by microstructures containing substantial amounts of non-martensitic austenite decomposition products. In the same gauge armor of higher hardness, a fibrous fracture has usually designated at least fairly well quench hardened material. Armor which is characterized by a fibrous fracture behaves in a ductile manner when subjected to ballistic shock at normal temperatures.

b. The crystalline fracture, in plates of hardness less than approximately 340-360 Brinell, designates armor which, because of incomplete quench hardening and the resulting presence of excessive amounts of high and/or intermediate transformation products, has relatively low impact strength at high rates of strain. A crystalline fracture may also be caused in even completely quench hardened material by temper brittleness or hardness in excess of the upper limits designated. Armor which breaks with a crystalline fracture tends to fail during room temperature ballistic shock tests.

c. The mixed fracture, in armor softer than the specified hardness range and free from temper brittleness, is caused by the presence of non-martensitic transformation products in lesser amounts than exists in wholly crystalline material. The fracture represents impact properties and ballistic shock performance intermediate between those of armor which breaks in a fibrous manner and armor which breaks in a crystalline manner.

Armor which is revealed by the fracture test to have broken with either a crystalline or mixed fracture is not considered acceptable for ballistic testing.

In Table II are listed the fibre fracture test ratings of the steel quality fractures as well as the data of the fibre fracture test. This has been done to illustrate two phenomena which should be realized whenever the fibre fracture test is to be conducted.

Study of the fibre ratings of the steel quality fractures will reveal that in the case of "D" and "E" quality plates characterized by mixed fractures, the transverse fractures showed appreciably less crystallinity than the corresponding longitudinal fractures. This material had been straightaway rolled and hence when fractured the laminations in the fractures perpendicular to the rolling direction were much deeper than those in the fractures parallel to the longitudinal direction. The effect of a deep lamination is to change the fracture of an incompletely quench hardened material from a brittle to a ductile break because of the plastic deformation initiated by slip along the inclusion plate surfaces. This phenomenon will be encountered again in the "V-Notch Charpy Impact Test" section of this report.

With the above situation in mind, fracture bars for the fibre fracture test were selected, in general, so as to secure longitudinal fractures. Comparison of these deeply notched, quickly broken fractures with the corresponding shallow notched, slowly broken steel quality fractures illustrates the second phenomenon. It is evident that crystallinity is much more pronounced in the fractures produced by the fibre test than in the companion steel quality fractures. Indeed, in some instances plates which are indicated by the shallow notched, slowly broken fractures to have been almost completely quench hardened have been revealed by the change in depth of notching and speed of fracturing to have been rather incompletely quench hardened. Further reference in this report to the fibre fracture test data will pertain only to the ratings achieved by the deeply notched, sharply impacted fracture bars. (Note: In the case of the Carnegie-Illinois 1½" plate no crystallinity was revealed by the fibre fracture test although a small amount was indicated by the steel quality fractures. The fibre rating of the latter test will be considered the true rating in this case.)

Although insufficient data preclude any attempt at statistical correlation between the various fibre fracture test ratings and response to low temperature ballistic shock, several trends are evident from inspection of Table II. Corroborating the correlation found in the case of the cast plates tested at Camp Shilo,[8] all plates having fibrous fractures possessed satisfactory ballistic shock properties at low temperatures, whereas plates whose fractures were largely crystalline (the 1½" plates only in this instance) usually failed the test. These trends are further emphasized upon reference to the data sheets of Inclosure A, wherein it can be seen that not a single shock failure occurred in the five series characterized by the fibrous fracture.

The question may be raised at this point as to whether or not the fibre test fractures of the two Van Dorn plates and the Youngstown plate can be considered fibrous in view of the one or more deep laminations present in the fractures. In these instances, from metallurgical examination plus low temperature V-notch Charpy tests with specimens that were free of laminations, it can be stated that little if any crystallinity would have been present had the fractures been devoid of laminations. Were it not for these additional data, which would not have been available for inspectors in the field, the results of the fibre fracture test for these plates would necessarily be considered inconclusive.

The data in Table II and Inclosure A also indicates that 2" plate characterized by fractures that are approximately 25%-60% crystalline usually passed the shock test administered at Camp Shilo. The apparently conflicting behavior of the Great Lakes series, wherein Plate 1X1 (5% crystallinity) failed under shock whereas Plate 1X4 (50% crystallinity) passed the test is due to the effect of the fracture laminations of this "E" quality steel upon the character of the fibre test fracture. Microstructurally the plates are equivalent and indicative of very poor quench hardening; and it is felt that had the steel been clean, the fibre fractures would both have been predominantly crystalline. The conclusion to be drawn from the fibre fracture data for the 2" plates is that the low temperature shock test at Camp Shilo for 2" plates was comparatively mild and inadequate for separating plate possessed of optimum shock resisting properties from those having borderline shock resistance.

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8. Watertown Arsenal Laboratory Report No. 710/534 - "Correlation of Metallurgical Properties with the Low Temperature Ballistic Shock Characteristics of 1" to 2" Low Alloy Cast Armor Tested at Camp Shilo" - 16 August 1943.

The effect of steel quality upon shock failure is illustrated by the Carnegie-Illinois $1\frac{1}{2}$" plate. Since failure under the impact of the non-penetrating slug was caused by a back spall, it would be suspected that the cause was poor steel quality. The "D" fracture rating assigned to this plate and the presence of only a small amount of crystallinity in the fractures of this material indicate that steel quality was the predominant cause of failure.

5. V-Notch Charpy Impact Test

The energy values and corresponding fracture descriptions of the V-notch Charpy test bars are recorded in Table II for ready comparison with the fibre fracture test ratings and the ballistic shock results. Charpy fractures are described in regard to presence of both crystallinity and laminations, with ratings similar to the fibre and steel soundness tests except that the presence of a deep lamination is further indicated by a notation after the soundness rating. The Charpy data are further represented graphically in Inclosure A, Figures 19 to 35, underneath photomicrographs of the microstructures photographed at locations within the plate sections which corresponded to the longitudinal axes of the Charpy bars. Thus, impact results can be readily compared to microstructure.

At the outset of this section a brief discussion is advisable as to the reasons for the low temperature Charpy tests.[9] It is the misconception of some people that the prime value of a Charpy test at a particular temperature is to determine an energy value which is to be considered as indicative of the impact resistance of the material at that temperature, and that, if a material is to be used in service at some particular temperature, the impact test should be run only at this temperature.

It has been recognized by investigators[10, 11, 12] that the most important result to be sought from impact testing a material at successively lower temperatures is the temperature at which the test specimen fracture changes from a ductile to a brittle type. The brittle fracture is indicative of poor shock resistance; fracture occurs without the absorption of appreciable energy by the material. Other factors, such as dimension of the piece, depth of notch, and strain rate, act similarly to temperature in causing the change from ductile to brittle behavior.

9. The V-notch charpy test is investigated and explained thoroughly in the following report written at this Arsenal: "Plastic Flow and Rupture of Metals - Third Partial Report" - 6 September 1943, WAL No. 732/10-2.

10. D. J. McAdam, Jr. and R. W. Clyne - "The Theory of Impact Testing ..." - A.S.T.M. 38, Part II (1938)

11. N. Davidenkoff - "Some Considerations on the Impact Testing Problem" - A.S.T.M. 38, Part II (1938)

12. See footnote 9, above.

In seeking to determine the room temperature impact properties of a material, especially as regards resistance to ballistic shock, the logical approach would appear to consist of breaking test specimens at room temperatur at higher and higher rates of strain and at determining the strain rate at which the material fractured brittlely; the higher this critical strain rate, the higher being considered the impact resistance of the material. Since it is not at present possible to achieve very high rates of strain by any impact testing device and since decreasing the temperature has an equivalent effect to raising the strain rate,[13] with a small decrease in temperature, moreover, being equivalent to a large strain rate increase, V-notch charpy specimens are tested at low temperatures to evaluate the resistance of material to high rates of strain.

Another point which must be recognized before critical inspection of the impact data in Table II is the effect of laminations upon the energy values and character of the fractures. It is readily apparent from comparisons in Table II of duplicate specimens broken at the same temperatures that the presence of a deep lamination causes an increase in the impact energy, and that this increase is more pronounced at and below the temperature of brittle failure than above this temperature, with the fracture being changed from crystalline to fibrous at and below the transition temperature. Several illustrative examples are as follows: Standard (Great Lakes) 1½" plate center of section specimens broken at 20°C.; Carnegie-Illinois 1½" plate center of section specimens broken at -40°C.; and Standard (Jones and Laughlin) 1½" plate center of section specimens broken at -70°C. All energy values which have been influenced by laminations should be disregarded. This was kept in mind when the Charpy energy versus temperature curves of Inclosure A were drawn (Note: The effect of the laminations might have been overcome to some extent had the notches been machined in the thickness direction).

Referring now to Table II and the curves of Inclosure A, it is seen that plates whose impact strengths at the center of the section as well as midway between the center and plate surface did not drop appreciably at -40°C. gave completely fibrous fractures in the fibre fracture test; whereas plates whose impact energy at both locations dropped rapidly as the temperature of testing was lowered from room temperature gave predominantly crystalline fractures in the fibre fracture test. The Carnegie-Illinois 1½" and 2" plates are illustrative of armor whose impact strength at -40°C. has decreased appreciably from the room temperature energy for specimens at the center of the section, although at the location midway between center and surface the room temperature impact value has been maintained at -40°C. The fibre fracture of the 1½" plate showed only a small amount of crystallinity; that of the 2" plate, about 25%. From an overall comparison between the fibre fractures and the fractures of the Charpy specimens, it is seen that the severity of the fibre fracture test for 1" to 2" plate, conducted at room temperature, is equivalent to that of a V-notch Charpy test conducted at some temperature between -10°C. and -40°C.

Correlation of the impact data with microstructure will be covered in the section dealing with microstructure, Section 9. It will be shown there that the maintainance of adequate room temperature impact resistance by specimens taken from the center of the plate and tested at temperatures down to

13. See footnote 9, page 15.

-40°C. is associated with a microstructure consisting entirely or almost entirely of tempered martensite, and that the decrease of impact energy with decrease of temperature before -40°C. is reached is due in plate softer than approximately 340 Brinell to the presence of high and/or intermediate temperature transformation products such as ferrite, pearlite, and bainite. By adequate room temperature impact energy is meant the impact value which is possessed by completely quench hardened plates of the same Brinell and similar mechanical treatment. This corroborates other data[14,15,16] obtained at this Arsenal. Thus, by performing V-notch Charpy tests at low temperatures, it can be determined whether or not a steel has been thoroughly quench hardened. This is the chief value of V-notch impact testing of armor plate. (Note: This is true providing the steel does not suffer from temper brittleness. Such steels, although thoroughly quench hardened, will lose impact energy with decrease in temperature.)

6. Macroscopic Examination

The macrostructures of the plates are illustrated by Figures 1 to 6. Ratings determined from the steel soundness fracture test are recorded under the photomacrographs of the etched macro bars corresponding to the steel soundness fractures. Descriptions of the etched sections are included in the data sheets of Inclosure A.

In many instances the macrostructures reveal the inclusion stringers responsible for the laminations and resulting fracture ratings of the plates. In some, the macrostructures are cleaner than would be expected from the evidence of the steel soundness fractures. This phenomenon, which has been seen on many occasions in the past, may be accounted for in great part by the difference in the number of planes tested by the two procedures. In a macro-etched section the inclusion content and distribution are revealed at only one plane through the steel, whereas the effect of a fracture in revealing the nonmetallic condition is, in a sense, three dimensional.

The directional characteristics of the plates, which were observed from the steel soundness fractures and listed in Table II, are illustrated by the photographs of the macroetched structures. The following plates are revealed to have been rolled in one direction predominantly. Both Standard (Great Lakes) 1½" plates, the Standard (Youngstown) plate, both Standard (Great Lakes) 2" plates, Ford Plate 2040-R, and Carnegie-Illinois Plate 129438-CTB and the Republic plate. The latter two plates were cross rolled; all others were straightaway rolled.

A particularly "woody" fracture was noted when the transverse fracture bars cut from the Republic plate were broken. The cause is revealed by the macroetched longitudinal section, which shows the presence of numerous short elongated inclusion stringers throughout the section of this predominantly unidirectionally rolled material.

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14. See footnote 9, page 15.

15. See footnote 2, page 3.

16. See footnote 8, page 14.

7. Microscopic Determination of Nonmetallics

In Figures 7 to 10 are photomicrographs illustrating the amount and distribution of inclusion stringers within each plate. In the data sheets of Inclosure A nonmetallic condition is correlated with corresponding macro-etched structure and steel soundness fracture ratings.

Although insufficient specimens were examined to expect a quantitative correlation between inclusion content and macrostructure and fracture rating (and this was not intended as a part of the investigation), the type inclusions responsible for the steel soundness ratings were detected in every instance except one (Disston 1" plate). The poor steel quality of all the Great Lakes plates, the Carnegie-Illinois 1½" plate, and the Youngstown plate was found to have been caused by long stringers of oxide type inclusions. An oxide type of inclusion was also seen to have been responsible for the laminations in the fractures of the Republic plate. The numerous stringers in the macrostructure of this plate, which are apparently the cause of the extreme "woodiness" of the longitudinal fracture, consist of thin elongated inclusions.

The quantity of inclusions seen microscopically in the two Van Dorn plates and the Ford plate was less than would be expected from macrostructure and fracture, but the distribution checked the results on macrostructure and fracture in each case. Centerline concentrations of thin elongated inclusions seen microscopically in both Van Dorn plates correlate with the centerline condition revealed by macroetching and fracture. Sulphide inclusions were found in the Ford plate in concentrations mainly at the center of the section, the same location where laminations were revealed by macrostructure and steel soundness fracture.

8. Hardenability

Results of the Jominy hardenability tests are recorded in Table IV and the data sheets of Inclosure A. The hardness survey data are plotted in Figures 11 to 17. Chemical analysis and Jominy heat treatment cycle are listed underneath the hardenability graph of each plate. The austenizing temperatures and time cycles used are those reported by the manufacturers on the CAS forms.[17] These data were lacking for the Jones and Laughlin plate and the Van Dorn plates. A temperature of 1600°F. was selected for the Jones and Laughlin Jominy bars since this was the temperature used by the company at that time. The Van Dorn Jominy bars were austenitized at 1675°F. in order to achieve complete solution of the carbides of these moderately high chromium-molybdenum steels.

In Table IV hardenability, as measured by Rockwell "C" hardnesses at various distances from the quenched end of the Jominy bar, is evaluated in terms of equivalent plate thickness.[18] This has been done using two separate hardenability criteria and two different quenching rates—still water and a water spray—for each criterion.

17. The Disston 1" plate Jominy bars were accidently austenitized at 1425°F. instead of 1450°F.

18. The substitution of equivalent plate thickness for hardnesses at various distances from the Jominy bar quenched end was accomplished by means of data and graphs reported by the Battelle Memorial Inst. in the report "Correlation of Cooling Velocity of the Standard Jominy Hardenability Test with the Cooling Velocity within the Cross Section of Plates" - John G. Kura and C. H. Lorig - Battelle Memorial Inst. 24 August 1942.

In Table IV are also listed data achieved by microscopic examination of one Jominy bar of each plate after polishing and etching the flat on which the hardness survey was made. By means of the microscopic data, the hardenability of each plate is listed in Table IV as adequate or inadequate depending on whether or not the material was capable of being quenched to a greater than 90% martensite structure at the center of the section. These data are for quenching efficiencies of both still water and a water spray.

The first hardness hardenability criterion to be discussed is Rockwell "C" 43. At the period when Jominy hardenability tests were being conducted on armor plate for the first time, it was found that armor having a minimum hardenability such that it could be quench hardened to at least Rc 43 at the center of the section gave passing ballistic shock performance. Material was therefore considered to have adequate hardenability if the Jominy bar had a hardness of Rc 43 or over at the distance from the quenched end which had the same cooling rate at 1300°F. as the center of the subject plate or casting when the material was quenched at the heat treating facility.

With the advent of the fracture test and increased production of armor thicker than 2", it was found that while this criterion was generally valid ballistically for plate in thicknesses up to 2" made from low alloy compositions, it was unreliable for application of the fracture test to low alloy armor of moderate hardenability and invalid for higher alloy, high hardenability armor (from which armor in thicknesses above 2" was fabricated) from the standpoint of both ballistics and the fracture test. The reason is shown in Table IV by the column headed "Percent Transformation Products Other Than Martensite at Rc 43". As indicated by the data for the Shilo plates, in armor having carbon contents over the range .20% to .30%, Rockwell "C" 43 can correspond to microstructures ranging from 100% martensite to 0% martensite.

In the column referred to above it should be noted that generally the lower the hardenability of the steel, as measured by number of 1/16" from the Jominy bar quenched end to Rc 43, the less the amount of transformation products other than martensite that is present at Rc 43. This is due mainly to the difference in the transformation characteristics and resulting hardnesses of the non-martensitic transformation products. Thus, for example, these products at Rc 43 in the Great Lakes 2" plate Jominy bar consisted entirely of ferrite containing round carbides aligned in rows or randomly distributed and ferrite containing carbide plates (pearlite), whereas the products in the Jones and Laughlin Jominy bar at Rc 44.5 consisted mainly of carbidic needles (bainite) with only traces of ferrite present. These microstructures as well as the Rc 43 structure of the 1" Van Dorn plate are shown in Figure 18.

Another factor which influences the amount of high and/or intermediate temperature austenite decomposition products present at Rc 43 is the hardness at 1/16" from the Jominy bar quenched end. The closer this value is to Rc 43, the less the amount of non-martensitic transformation products formed. An example is the comparison between the Carnegie-Illinois 2" plate and the Ford 2" plate, both of which had the same types of products at Rc 43. In the case of the Disston plates, moreover, no high or intermediate temperature transformation products were present at Rc 43, the quenched end hardnesses being only 44 (1½" plate) and 45.5 (1" plate).

It should also be noted, just as in the Jones and Laughlin—Great Lakes example cited above, that the types of austenite decomposition products will be different at Rc 43 for a high hardenability steel than for a low alloy steel of only moderate hardenability. Experience has shown that a low alloy steel plate containing a certain amount of high and intermediate temperature transformation products, as revealed in the tempered structure by the quantity of ferrite present, can have good ballistic properties, whereas the tempered microstructure of a high hardenability steel of the same hardness (in a thicker section, of course), although devoid of ferrite, can give poor shock resistance because of the presence of detrimental transformation products which are not discernible in the tempered microstructure. Just how much of each of the various high and intermediate temperature transformation products is permissible in armor is not known at this date. By the fibre fracture test, however, the amount is limited to that quantity which will not reduce materially the shock properties of the steel at high rates of strain.

In summation of the above paragraphs, it can be stated that Rc 43 is an unsatisfactory hardenability criterion for both low and high alloy armor since the amount of high and/or intermediate temperature austenite decomposition products present at this as quenched hardness, depending on the factors described above, can vary from 0% to 100%. Further, one reason why this criterion was usable for low alloy moderate hardenability armor although not adequate for higher alloy, high hardenability material is the much smaller amount of transformation products (other than martensite) present in the first type of steel at Rc 43.

The second hardenability criterion is the hardness on the hardenability graph at which an abrupt hardness drop begins. From Table IV it can be seen that, for low alloy moderate hardenability steel, this hardness is equivalent to a microstructure containing less than 10% of high and/or intermediate temperature transformation products (In the Shilo plates, usually even less than 5%.). Therefore, to achieve microstructures that are completely or essentially completely martensite, this criterion can be used for low alloy moderate hardenability steels.

Referring to the data for the high hardenability material examined—the Jones and Laughlin, Youngstown, and Van Dorn 1½" plates and the American Car 1" plate—even this criterion is found to be invalid for such armor. The structure is already only 90% martensite at several 1/16" before the hardness at which the abrupt hardness change has occurred. Moreover, instances have been seen at this Arsenal whereby high alloy material which showed very little if any drop in hardness at 40/16" from the Jominy bar quenched end was found unsuitable for armor in thicknesses that apparently should have been capable of being quench hardened at the plate center to the Jominy bar 40/16" hardness.

Recently a test specimen has been developed in the laboratory to determine the hardenability of armor steels not in terms of as quenched hardness but instead in terms of ability to give a fibrous fracture. The specimen dimensions are length—3", width—2", and thickness—.6" to .7". It is austenized and end quenched in the same manner as the Jominy bar. Following end quenching the test bar is tempered to the desired hardness, nicked for a depth of 1/8" along the lengthwise centerline of a 3"x2" face, and fractured by a quick blow. The hardenability of the steel is recorded as maximum distance from the quenched end at which the fracture is still wholly fibrous.

From comparison with standard Jominy bars, the cooling rates at various distances from the quenched end have been determined. The cooling rates of the end quench fracture bar have been found to be a little slower than the cooling speeds of Jominy bars at corresponding distances from the quenched end. By substituting equivalent plate thickness for the cooling rate at which fibre is maintained in the end quenched fracture bar, the hardenability can be expressed as maximum thickness of plate that will give a fibrous fracture upon being quenched (with specified quenching efficiency) and drawn to the hardness of the tempered end quench fracture bar.

By performing end quench fracture bar tests, the ability of a steel to develop a fibrous fracture in various thicknesses of armor and at various hardness levels can be determined in a direct manner. The question as to how much high and/or intermediate temperature transformation products can be tolerated can be answered by correlation of fracture bar microstructure with fracture appearance. The influence of other factors that affect the attainment of fibre, such as retained austenite and temper brittleness, can be determined. This method, in conjunction with the standard Jominy test, is now being used for hardenability evaluation of armor steels.

Attention should now be directed to Table IV in order to evaluate the hardenability of each of the seventeen plates examined. The criterion used will be the Jominy bar hardness at which the structure is >90% martensite. In all instances except for the four high hardenability plates referred to previously, this criterion is equivalent to the hardness at the beginning of the drop in the Jominy curve. Adequateness of hardenability is stated in the last two columns of Table IV.

It is seen that only five plates possessed sufficient hardenability for still water quenching—the Van Dorn and American Car 1" plates, and the Jones and Laughlin, Youngstown, and Van Dorn 1½" plates. The Carnegie-Illinois 1" plate was capable of being satisfactorily quench hardened throughout the section only by means of a water spray (Quenching efficiency of H=1.8) or quenching practice of equal efficiency. The steels used for 1½" and 2" plates by Carnegie-Illinois, Disston, Great Lakes, and Republic were so deficient in hardenability that the plates could not be quench hardened at the center to even Rc 43.

In view of the above results it was decided to end quench some of the Jominy bars again, this time from austenitizing temperatures higher than those formerly used. The plate identifications and austenitizing temperatures of the bars are as follows: Disston 1" and 1½" plates, 1600°F.; Carnegie-Illinois 1" and 1½" plates, 1675°F.; American Car 1" plate, 1675°F.; Great Lakes 1½" plate number 1X4, 1675°F.; and Republic 1½" plate, 1675°F.

Increase in hardenability was detected only in the cases of the Disston 1" and 1½" plates and the Great Lakes plate, and only for the Disston 1" plate was it significant. The data for this plate, plotted in Figure 11, indicates that the plate could have been quenched to >90% martensite at the center of the section had it been quenched efficiently (H=1.8) from 1600°F.

To determine the effect of centerline segregation upon the centerline hardenability, many of the Jominy bars were ground again to a depth of .050" at locations ½" from the center of the plate section. That segregation had lowered the hardenability of some of the plates was shown by the following increases in the lengths of the straight line portions of the Jominy curves: Carnegie-Illinois 1½" plate, 2/16"; Disston 1½" plate, 1/16"; Great Lakes 1½" plates, 1/16" to 2/16"; Republic 1½" plate, 1/16"; and Great Lakes 2" plate, 2/16".

9. Metallographic Examination

Photomicrographs illustrating the microstructures of the plates at X200 and X1000 are included in Inclosure A as part of Figures 19 to 35. The photomicrographs show the microstructure of each plate except one at the center of the section and also, in the case of the 1½" and 2" plates, the structure midway between the plate center and surface whenever this varied from the structure at the center of the section. In the "Structure and Remarks" sections of Data Sheets 1 to 17, Inclosure A, microstructures are discussed and correlated with the ballistic results and metallurgical data obtained by this investigation.

As is to be expected from the Jominy hardenability data, Figures 19 to 35 show that large amounts of non-martensitic austenite decomposition products occurred in most of the plates during the quenching operations. The center of the section being the region of slowest cooling rate during a normal quench, the amount of high and intermediate temperature transformation products was greater at this location than elsewhere in the section except in the case of the Carnegie-Illinois 1" plate. The photomicrographs of this plate (Figure 20) show increasing amounts of non-martensitic transformation products from one plate face to the other, indicating that the plate had been quenched more severely at the first face than at the second.

It is evident also that many of the plates are banded appreciably, especially at the center of the section. In those instances where banded structures contained non-martensitic transformation products, the X1000 photomicrographs were taken at the bands which contained these products to the greatest extent. These are the lighter etching bands in the X200 photomicrographs.

The banding revealed by metallographic examination correlates with the superiority in hardenability at ½" from the center over that at the center of the section noted in the previous section of this report. In the case of the Carnegie-Illinois 1½" plate the effect of banding in lowering the hardenability at the center of the section is significant, for this, plus efficient quenching practice, explains why the material was almost completely quench hardened midway between the center and the surface although from the hardenability data obtained at the center of the section the steel was capable of being quench hardened with a water spray (H=1.8) to >90% martensite in a plate of only 1" thickness. The equivalent plate thickness of this steel, judged by hardenability data obtained ½" from the center of the section, is 1-5/16" (water spray quench and >90% martensite criterion).

An important fact in regard to interpretation of tempered microstructures can be pointed out at this time. The quantity of free ferrite is an unreliable yardstick for estimation of amount of non-martensitic austenite decomposition products in a plate unless the relationship between quantity of free ferrite and quantity of non-martensitic products for the plate has first been ascertained by microscopic examination of the Jominy bar. Some indication of the big difference which can exist between the ferrite contents of the non-martensitic products of two different steels is afforded by Figure 18. Microstructures of the seventeen plates examined were described after examination of the corresponding as quenched Jominy bars.

Referring now to Inclosure A, it is seen from comparison of the microstructures with the corresponding fibre ratings that in every instance except one the presence of appreciable amounts of non-martensitic austenite decomposition products is associated with crystallinity in the fibre test fractures, the amount of crystallinity increasing with increase in the extent of the products throughout the section. The exception is the Republic plate which, although characterized by a completely fibrous fracture, contains a great deal of non-martensitic transformation constituents at the center of the section. The explanation for the fibrous fracture of this plate is the low hardness (220 Brinell) which may have been assisted also by the extreme "woodiness" of the fracture.

A more detailed and more informative correlation of microstructure with impact properties is obtained by comparison between the photomicrographs and the corresponding V-notch Charpy impact curves. First, however, it should be noted that whereas in most instances the photomicrographs of the microstructures midway between plate center and surface are fairly typical of the whole of the Charpy specimens machined from this location, the photomicrographs of the Great Lakes $1\frac{1}{2}$" plates and the Disston $1\frac{1}{2}$" plates illustrate only the average structures in the corresponding Charpy specimens because of abrupt structural variations in the specimens caused by banding and ingotism.

In Section 5, "V-Notch Charpy Impact Test", the characteristics of the Charpy energy versus temperature curve that designate essentially complete quench hardening in armor tempered to below approximately 340 Brinell have been stated, based on previous data obtained at this Arsenal. These are: room temperature energy equivalent to that of similarly mechanically processed material of the same Brinell that is known to have been completely quench hardened, and maintenance of this energy down to -40°C. These characteristics are possessed by both impact curves of the Jones and Laughlin plate and by the midway region impact curves of the Carnegie-Illinois $1\frac{1}{2}$" and 2" plates and the Van Dorn $1\frac{1}{2}$" plate. The corresponding photomicrographs indicate also that these regions had been essentially completely quench hardened.

In most instances in Figures 19 to 35 the presence of appreciable amounts of non-martensitic austenite decomposition products is associated not only with inferior room temperature impact energy but also with rapid decrease of energy as the testing temperature was lowered. The center of section region of the Carnegie-Illinois 2" plate is an example of incompletely quench hardened material that possesses adequate room temperature energy but loses energy as the temperature falls.

Another point evident from the correlation of microstructure with the data of both impact tests is that superiority of one analysis over another, of the compositions tested at Camp Shilo, was due to superiority in hardenability alone. With adequate hardenability satisfactory quench hardening, good impact strength at high rates of strain, and good shock performance were obtained. Plates characterized by poor hardenability possessed excessive amounts of high and intermediate temperature transformation products, poor impact toughness (except the Republic plate), and generally poor resistance to cracking upon being shock tested. In the case of the Disston plates, high nickel content was unable to overcome the deleterious effects of poor hardenability and intercritical quenching.

It is also seen that the V-notch Charpy test is superior to the fibre fracture test for the accurate determination of degree of quench hardening at all hardness levels of the tempered armor. The value in knowing whether or not armor is completely quench hardened is in being able to predict the impact toughness of the same material at some higher Brinell. Armor which contains non-martensitic products and gives a fibrous fracture because of low hardness may, at some higher hardness, break with a crystalline or mixed fracture.

10. Summarizing Discussion

a. Shock Test

Due to the scarcity of alloying elements, particularly chromium and molybdenum, available for utilization in the production of armor at that time, most of the plates tested at Camp Shilo were deficient in alloy content and therefore possessed poor hardenability. This was reflected in the microstructures of these plates by the presence of excessive amounts of high and intermediate temperature transformation products. Impact properties were therefore poor, and whereas at room temperature similar quality armor had been usually passing the ballistic shock test, the increased severity of the test caused by the low temperatures resulted in ballistic failures among the 1" and 1½" plates.

On the other hand, plates which were essentially quenched out (because of adequate hardenability) possessed good impact strength at high rates of strain and behaved just as well ballistically at low temperatures as similar plates made by the same companies had behaved at normal temperatures. Few failures occurred at Camp Shilo among the 2" plates, whose impact properties were generally poor, but this is attributed to the mildness of the test.

Other causes of shock failures were high and non-uniform hardness and poor steel quality. High nickel content was found to be inadequate in the case of the Disston plates to overcome the effects of non-martensitic constituents.

b. PTP Test

A large increase in the number of PTP failures was encountered when armor similar to that found acceptable at room temperature was tested at subnormal temperatures. The critical range at which spalling occurred as the temperature was lowered was -25°F. to -30°F. The metallurgical investigation revealed the necessity for better steel soundness and lower hardness levels for low temperatures as compared to normal temperatures. The data indicate that for use at subnormal temperatures armor in thicknesses above as well as below 1-1/8" should have better than "D" steel soundness rating.

Although some $1\frac{1}{2}$" plates of "D" steel soundness rating spalled during the projectile-through-the plate test, many $1\frac{1}{2}$" plates characterized by "D" and even "E" steel soundness ratings and some 2" plates of "D" fracture rating did not spall when penetrated with the 37 mm M51 APC projectiles required by the tests for these plate thicknesses. These results indicate that the projectile-through-the plate tests given the $1\frac{1}{2}$" and 2" plates were inadequate for revealing the spalling tendencies of poor steel soundness plates.

Records

The original records of this investigation are contained in Laboratory Notebook No. 9, pages 112 to 131.

TABLE I

Shilo Cold Test Rolled Armor Examined at Watertown Arsenal

Company	Heat No.	Plate No.	Thickness	Type Chemistry	Ballistics Shock	Ballistics PTP
		1" Plates				
Disston	3339	1	1.02"	Ni-Mo	Failed	No Test
Carnegie-Illinois	B-52607	4-2-T-4	1.00"	Ni-Cr-Mo	Passed	Failed
Van Dorn Iron Works	H-40297	1	1.02"	Ni-Cr-Mo	Passed	Passed (-16°F.) Failed (-34°F.)
American Car & F'dry	H-50196 (Carburized Armor)	1702-7	1.00"	Ni-Cr-Mo	No Test	Passed
		1½" Plates				
Carnegie-Illinois	22345	129438-CTB	1.51"	Mn-Ni-Cr-Mo	Failed	No Test
Disston	22851	2	1.51"	Ni-Mo	Failed	No Test
Standard (Great Lakes)*	GSG-724	1X4	1.51"	Si-Cr-Mo-Zr	Failed	No Test
Standard (Great Lakes)*	GSG-724	1X5	1.50"	Si-Cr-Mo-Zr	Failed	No Test
Republic	RH-50307G	-	1.48"	Ni-Cr-Mo	Passed	Failed
Disston	22851	5	1.50"	Ni-Mo	Passed	Passed
Standard (Jones & Laughlin)*	GSJ-335	M1X3	1.51"	Mn-Mo	Passed	Passed
Standard (Youngstown)*	GSY-75-10	1X5	1.51"	Mn-Mo	Passed	Passed
Van Dorn Iron Works	H-20542	4	1.55"	Ni-Cr-Mo	Passed	Passed
		2" Plates				
Standard (Great Lakes)*	GSG-635	1X1	2.05"	Si-Cr-Mo-Zr	Failed	Failed
Carnegie-Illinois	15378	TB-143317	2.02"	Mn-Ni-Cr-Mo	Passed	Failed
Standard (Great Lakes)*	GSG-635	1X4	2.03"	Si-Cr-Mo-Zr	Passed	Failed
Ford	9282E	2040-R	1.98"	Mn-Cr-Mo	Passed	Passed

*The steel source is in parenthesis.

Company	Heat No.	Plate No.	Thickness	Type Composition	BRINELL HARDNESS 1/4" from Surface	Midway Surface - Center	Center	Steel Quality[1] Fracture R... Long.	Tr...
Disston	3339	1	1.02"	Ni-Mo	316	316	302	B-	
Carnegie-Illinois	B-52607	4-2-T-4	1.00"	Ni-Cr-Mo	321 One Side 321 352 Other Side 352		331	B-	
Van Dorn Iron Works	B-40297	1	1.02"	Ni-Cr-Mo	255	269	269	B- Centerli...	
American Car & Foundry	B-50196	1702-7	1.00"	Ni-Cr-Mo	514 Case Face - 401 Core Face (Surface Brinells)		401	B	
Carnegie-Illinois	22345	12943- CTB	1.51"	Mn-Ni-Cr-Mo	311	302	285	C-	
Disston	22851	2	1.51"	Ni-Mo	255	238	232	B	
Standard (Great Lakes)	GSG-724	1X4	1.51"	Si-Cr-Mo-Zr	269	262	245	B	
Standard (Great Lakes)	GSG-724	1X5	1.50"	Si-Cr-Mo-Zr	269	259	248	B	
Republic	BH-503070	-	1.48"	Ni-Cr-Mo	245	226	220	C- (Woody)	
Disston	22851	5	1.50"	Ni-Mo	251	255	255	B-	
Standard (Jones & Laughlin)	GSJ-335	M1X3	1.51"	Mn-Mo	285	285	285	B-	
Standard (Youngstown)	GSY-75-10	1X5	1.51"	Mn-Mo	259	265	262	D Centerli...	
Van Dorn Iron Works	B-20542	4	1.55"	Ni-Cr-Mo	248	248	248	D Centerli...	
Standard (Great Lakes)	GSG-635	1X1	2.05"	Si-Cr-Mo-Zr	281	269	238	B	
Carnegie-Illinois	15378	TB-143317	2.02"	Mn-Ni-Cr-Mo	302	302	297	B	
Standard (Great Lakes)	GSG-635	1X4	2.03"	Si-Cr-Mo-Zr	285 One Side 277 277 Other Side 248		235	B	
Ford	92828	2040-R	1.98"	Mn-Cr-Mo	265	265	269	D Centerli...	

(1) See Appendix A for descriptions of steel soundness fracture ratings. (2) ●

(2) Descriptions of fibre fracture rating are as follows: (2) ▲

F = Fibrous FC = 40% to 60% C, balance F Cf = Mostly C, some F (2) ■

C = Crystalline Fc = Mostly F, some C Cfe = C, fibrous edge

 ..., AND V-NOTCH CHARPY IMPACT ...

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...pe ...po-...ion	BRINELL HARDNESS 1/4" from Surface	Midway Surface - Center	Center	Steel Quality[1] Fracture Rating Long.	Trans.	Directional Characteristics from the Rolling Process	Fibre Fracture Ratings[2] Slow Break Long.	Slow Break Trans.	Impact Long.	Lon... En... (Ft.-...
										1" PL...
...Mo	316	316	302	B-	C-	Uniform	F	Fc ● (Trace C)	Fc (30% C)	49.1
...Cr-...o	321 One Side 352 Other Side	321 352	331	B-	B-	Uniform	F	Fc (Trace C)	Fc ▲ (5% C)	50.1
...Cr-...o	255	269	269	B- Centerline	C	Uniform	F	F ●	F ●	67.3
...Cr-...o	514 Case Face - 401 Core Face (Surface Brinells)		401	B	B	Uniform	C	C	-	24.7
										1½" PL...
...Ni-...Mo	311	302	285	C-	D	Uni-directional	Fc (Trace C)	Fc ● (10% C)	F	135.0 •70.9
...Mo	255	238	232	B	B	Uniform	Fc (30% C)	Fc (Trace C)	Cfe (90% ●)	103.5 •80.1
...Cr-...Zr	269	262	245	E	E	Uni-directional	Fc ● (25% C)	Fc ● (10% C)	Cf ● (65% C)	104.0 •75.2
...Cr-...Zr	269	259	248	E	E	Uni-directional	Fc ● (25% C)	Fc ● (5% C)	Cf ● (65% C)	84.1 •50.7
...Cr-...Mo	245	226	220	C- (Woody)	D	Uni-directional	F	F ●	F	175.0 •142.0
...Mo	251	255	255	B-	B	Uniform	Fc (5% C)	F	FC ▲ (60% C)	89.0 •91.5
...Mo	285	285	285	B-	B-	Uniform	F	F	F	47.1 •58.2
...Mo	259	265	262	D Centerline	C	Uni-directional	F	F	F ●	77.1 •70.2
...Cr-...Mo	248	248	248	D Centerline	D	Uniform	F ●	F ●	F ●▲	77.1 •75.1
										2" PL...
...Cr-...Zr	281	269	238	E	E	Uni-directional	Fc ● (Trace C)	F ●	Fc ● (5% C)	151. •77.
...Ni-...Mo	302	302	297	B	B	Uniform	Fc (10% C)	Fc (Trace C)	Fc (25% C)	59. •50.
...Cr-...Zr	285 One Side 277 Other Side	277 248	235	E	E	Uni-directional	Fc ● (10% C)	Fc ● (Trace C)	FC ●■ (50% C)	78. •79.
...Cr-...Mo	265	265	269	D Centerline	D	Uni-directional	Fc ● (25% C)	Fc ● (5% C)	FC ■ (60% C)	88. •105.

...steel soundness fracture ratings.
...ng are as follows:
...balance F Cf = Mostly C, some F
... C Cfe = C, fibrous edge

(2) ● Fracture contains one or more deep laminations.
(2) ▲ Transverse fracture instead of longitudinal as desig...
(2) ■ Fracture bar was nicked at both faces as well as at ... sides.

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...re Ratings		V-NOTCH CHARPY IMPACT TEST									
		Long. Specimen, +20°C.			Trans. Specimen, +20°C.			Trans. Specimen, -10°C.			
...ns.	Impact Long.	Energy (Ft.-lbs.) (3)	Quality Rating (4)	Fibre Rating (5)	Energy (Ft.-lbs.) (3)	Quality Rating (4)	Fibre Rating (5)	Energy (Ft.-lbs.) (3)	Quality Rating (4)	Fibre Rating (5)	(...
		1" PLATES									
● ...e C)	C (30% C)	49.1, 50.5	B, B	Fc, F	37.6, 35.8	B, B	F, F	30.1, 17.2	B, B	Fc, Cf	1...
...e C)	Fc ▲ (5% C)	50.1, 47.3	B, B	F, F	29.5, 27.9	B, B	F, F	26.5, 26.1	B, B	Fc, F	1...
●	F ●	67.3, 56.0	D', B	F, F	57.6, 58.4	C', D'	F, F	56.6, 56.7	D', D'	F, F	6...
	-	24.7, 25.2	B, B	Cf, Cf	16.1, 14.6	B, B	Cfe, Cfe	12.9, 12.9	B, B	Cfe, Cfe	
		1½" PLATES									
● ...% C)	F	135.0, 92.0	D', D'	F, F	53.5, 40.7	D', C'	F, F	38.2, 36.6	B, D	F, Fc	2...
		•70.9, 67.5	D', D'	F, F	•34.5, 39.1	B, D	F, F	•33.9, 46.5	D, D'	F, F	•5...
...e C)	Cfe (90% C)	103.5, 87.5	B, B	F, Fc	61.9, 59.1	B, B	Fc, Fc	32.6, 34.5	B, B	Cf, Cf	2...
		•80.1, 82.0	B, B	Fc, Fc	•50.1, 47.1	B, B	Fc, Fc	•27.6, 46.8	B, B	Cf, Fc	•2...
● ...% C)	Cf ● (65% C)	104.0, 92.0	C', D'	Fc, F	44.4, 40.7	D, B	Fc, Fc	38.4, 44.9	D', D'	Cf, Cf	1...
		•75.2, 79.5	C', D'	Fc, F	•35.0, 37.4	B, B	Fc, Fc	•25.8, 28.0	C, D	Cf, Cf	•1...
● ...% C)	Cf ● (65% C)	84.1, 71.3	D, B	Fc, Fc	40.4, 44.4	B, D'	Fc, Fc	21.5, 28.0	B, B	Cf, Cf	1...
		•50.7, 68.8	C, D'	Fc, Fc	•35.5, 35.8	C, C	Fc, Fc	•26.2, 24.7	C, B	Cf, Cf	•1...
●	F	175.0, 140.5	E', E'	F, F	47.5, 56.4	BW, BW	F, F	56.4, 50.7	BW, BW	F, F	4...
		•142.0, 160.0	D', E'	F, F	•43.2, 47.1	BW, BW	F, F	•45.8, 42.0	BW, BW	F, F	•4...
	FC ▲ (60% C)	89.0, 87.5	B, B	F, F	50.3, 54.6	B, D'	Fc, F	35.0, 27.7	C', B	Cf, Cf	3...
		•91.5, 91.5	B, B	F, F	•49.1, 49.1	B, B	F, Fc	•46.6, 25.0	B, B	Fc, Cf	•2...
	F	47.1, 70.9	B, B	F, F	74.2, 54.6	C', B	F, F	55.5, 57.1	C', B	F, F	5...
		•58.2, 56.4	B, B	F, F	•43.2, 47.1	B, B	F, F	•43.2, [illegible]	B, B	F, F	•4...
	F ●	77.1, 75.1	C, C	F, F	47.8, 44.0	B, B	F, F	45.1, 45.8	C, B	F, F	4...
		•70.2, 71.3	B, B	F, F	•40.2, 40.7	B, B	F, F	•38.2, 41.4	B, B	F, F	•3...
●	F ●▲	77.1, 75.6	D', C'	F, F	67.1, 76.9	D', D'	F, F	65.9, 73.2	E', E'	F, F	6...
		•75.1, 79.1	B, B	F, F	•67.1, 70.2	B, B	F, F	•64.1, 66.6	B, B	F, F	•6...
		2" PLATES									
●	Fc ● (5% C)	151.5, 111.5	E', E'	F, F	31.8, 31.8	E, E	F, F	40.7, 27.9	E', E	F, Fc	3...
		•77.7, 79.3	C, C	Fc, Fc	•36.1, 34.7	E, D'	F, F	36 , 42.4	C', C'	F, Fc	3...
...e C)	Fc (25% C)	59.8, 60.6	B, B	F, F	45.6, 45.8	B, B	F, F	45.9, 44.1	B, B	F, F	2...
		•50.8, 54.6	B, B	F, F	•43.1, 46.1	B, B	F, F	•48.0, 44.1	B, B	F, F	•4...
● ...e C)	FC ●● (50% C)	78.1, 97.1	C', D'	Fc, Fc	35.2, 42.4	E, E'	Fc, Fc	29.8, 34.0	D', D'	Fc, FC	3...
		•79.5, 80.1	D', D'	F, F	•34.2, 37.4	D', C	F, F	•39.2, 35.0	D', D'	F, Fc	•3...
● ...% C)	FC ● (60% C)	88.0, 92.8	C, C	F, F	44.2, 41.5	B, C	F, Fc	32.6, 36.6	D, C'	FC, Fc	2...
		•105.6, 93.5	C, B	F, F	•43.1, 36.0	B, B	Fc, Fc	•20.5, 38.2	B, B	Cf, Fc	•1...

...laminations.
...itudinal as designated.
...es as well as at both

(3)• Charpy specimens that were machined from the region midway betwe... the plate center and surface.

(4) Same meaning as (1) except that C', D', and E' signify that fra... tures contain one or more deep laminations.

2

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T TEST

men. -10°C. (4) Quality Rating	(5) Fibre Rating	Trans. Specimen. -40°C. (3) Energy (Ft.-lbs.)	(4) Quality Rating	(5) Fibre Rating	Trans. Specimen. -70°C. (3) Energy (Ft.-lbs.	(4) Quality Rating	(5) Fibre Rating	Ballistic Tests Temp.	(6) Shock	(7) PTP
, D	Fc, Cf	15.9, 20.1	B, C	Cfe, Cfe	15.5, 12.0	B, B	Cfe, C	-29°F.	Failed (Back Spall)	No Test
, B	Fc, F	19.8, 22.4	B, B	Fc, Fc	12.9, 13.5	B, B	Cfe, Cfe	-27°F.	Passed (2" Crack)	Failed
, D'	F, F	60.4, 61.1	D', D'	F, F	31.2, 47.8	C, D'	Fc, Fc	-16°F. -34°F.	Passed Passed	Passed Failed
, B	Cfe, Cfe	- , 10.4	B, B	C, C	11.2, 10.7	B, B	C, C	+31°F.	No Test	Passed (Allowable Back Spall
, D	F, Fc	20.8, 84	B, D'	Cf, Fc	20.5, 15.5	B, B	Cfe, Cfe	-34°F.	Failed (Back Spall)	No Test
, D'	F, F	*53.7, 35.5	D', D'	F, F	*26.5, 31.8	B, C	Fc, Fc			
, B	Cf, Cf	27.3, 26.5	B, B	Cf, Cfe	17.8, 19.3	B, B	C, C	-25.6°F	Failed (Cracking)	No Test
, B	Cf, Fc	*20.8, 21.5	B, B	Cfe, Cfe	*14.5, 21.5	B, B	C, C			
, D'	Cf, Cf	18.3, 19.4	B, D	Cfe, Cfe	19.1, 11.5	D', B	Cfe, C	-22°F.	Failed (Shattered)	No Test
, D	Cf, Cf	*16.1, 13.9	B, B	Cfe, Cfe	*12.9, 8.1	B, B	C, C			
, B	Cf, Cf	18.7, 18.7	D, B	Cf, Cfe	12.7, 11.5	B, B	C, C	-18°F.	Failed (Shattered)	No Test
, B	Cf, Cf	*13.9, 14.5	B, B	Cfe, Cfe	*13.6, 10.1	B, B	C, C			
, BW	F, F	48.4, 46.5	CW, BW	F, Fc	19.4, 24.3	B, B	Cf, Cfe	-34°F.	Passed	Failed
, BW	F, F	*42.0, 43.1	BW, BW	F, F	*37.7, 39.1	BW, BW	Fc, Fc			
', B	Cf, Cf	30.3, 26.4	B, B	Cf, Cfe	14.8, 19.3	B, B	Cfe, C	-25.5°F	Passed	Passed
, B	Fc, Cf	*20.5, 40.7	B, B	Cfe, Fc	*26.5, 21.5	B, B	Cfe, Cfe			
', B	F, F	52.4, 57.5	B, B	F, F	33.9, 59.1	B, D'	FC, F	-30°F.	Passed	Passed
, B	F, F	*41.5, 46.6	B, B	F, F	*40.7, 34.2	B, B	Fc, FC			
, B	F, F	46.5, 45.8	D', D'	Fc, F	22.9, 27.4	B, D'	FC, FC	-16.5°F	Passed	Passed
, B	F, F	*31.2, 27.7	B, B	FC, FC	*15.5, 20.1	B, B	Cfe, Cfe			
, E'	F, F	69.3, 69.6	D', E'	F, F	56.4, 58.2	E', E'	F, F	-30°F.	Passed	Passed
, B	F, F	*62.8, 62.1	B, C	F, F	*46.1, 39.1	C, C	FC, FC			
, E	F, Fc	33.4, 38.9	E, E'	Fc, Fc	29.5, 14.8	E, D'	Fc, Cf	-15°F.	Failed (Cracking)	Failed
, C'	F, Fc	32.6, 34.4	D', D'	Fc, F	18.1, 20.8	C, C	Cfe, Cfe			
, B	F, F	25.8, 29.7	B, B	FC, FC	20.6, 26.4	B, B	Cf, FC	-30°F.	Passed	Failed
, B	F, F	*44.1, 43.2	B, B	F, F	*31.7, 38.9	B, B	FC, Fc			
, D'	Fc, FC	30.3, 23.9	D', D'	FC, Fc	11.1, 12.4	C', D'	Cfe, C	-15°F.	Passed	Failed
, D'	F, Fc	*[illegible].2, 38.9	C', D'	FC, Fc	*26.7, 32.8	D', C'	Cf, Fc			
, C'	FC, Fc	21.7, 18.3	C, B	Cf, Cf	17.8, 15.5	B, B	Cfe, Cfe	-26°F.	Passed	Passed
, B	Cf, Fc	*18.5, 29.1	B, B	Cfe, FC	*15.5, 14.5	B, B	C, C			

ion midway between

signify that frac-

(5) Same as (2).

(6) No cracking unless so stated.

(7) All PTP failures due to excessive back spalling. No spalling present in passing plates unless so stated.

3

Table III

Effect of Reduction in Temperature upon

Spalling Revealed by the Projectile-Through-the Plate Test

1" Plate

Carnegie Series

Temp.	Ballistic Result	Soundness Fracture	BHN
-18°F	No B.S.	—	-
-19°F	No B.S.	—	-
-27°F	Failing B.S.	B	352-321

Disston Series

Temp.	Ballistic Result	Soundness Fracture	BHN
-22°F	No B.S.	—	-
-27°F	No B.S.	—	-
-29°F	No Test	C-	316-302
-30°F	Allowable B.S.	—	-

Van Dorn Series

Temp.	Ballistic Result	Soundness Fracture	BHN
(-8.5°F (-30°F	No B.S.	—	-
-31°F	No B.S.	—	-
-31°F	No B.S.	—	-
(-16°F	No B.S.		
(-34°F	Failing B.S.	C	255-269

1½" Plate

Republic Series

Temp.	Ballistic Result	Soundness Fracture	BHN
-23°F	No B.S.	—	-
-24°F	No B.S.	—	-
-33°F	Allowable B.S.	—	-
-34°F	Failing B.S.	D	245-220

2" Plate

Carnegie Series

Temp.	Ballistic Result	Soundness Fracture	BHN
-25°F	No B.S.	—	-
-25°F	Borderline B.S.	—	-
-29°F	Failing B.S.	—	-
-30°F	Failing B.S.	B	302-297

Note: A similar increase of spalling, caused by hardness, with reduction of temperature has been noticed by the British in carefully controlled experiments. In their studies 1½" plates of the same hardness were fired at successively higher temperatures, beginning at about -40°F.

Company	Heat No.	Plate No.	Thickness	Type Chemistry	Hardness 1/16" from Quenched End - Rc	No. of 1/16" From Quenched End at Which High or Intermediate Temperature Transformation Begins
Disston	3339	1	1.02"	Ni-Mo	45.5	1*
Carnegie-Illinois	B-52607	4-3-2-4	1.00"	Ni-Cr-Mo	48.5	3
Van Dorn Iron Works	H-40297	1	1.02"	Ni-Cr-Mo	49	4
American Car & F'dry	H-50196	1792	1.00"	Ni-Cr-Mo	50.5	8
Carnegie-Illinois	22345	129438-CTB	1.51"	Mn-Ni-Cr-Mo	45.5	4
Disston	22851	2	1.51"	Ni-Mo	44	1*
Standard (Great Lakes)	GSG-724	1X4	1.51"	Si-Cr-Mo-Zr	48	4
Standard (Great Lakes)	GSG-724	1X5	1.50"	Si-Cr-Mo-Zr	48.5	-
Republic	RH-503070	-	1.48"	Ni-Cr-Mo	4[illegible].5	3
Disston	22851	5	1.50"	Ni-Mo	4[illegible].5	-
Standard (Jones & Laughlin)	GSJ-335	MLX3	1.51"	Mn-Mo	50.5	11
Standard (Youngstown)	GSY-75-10	1X5	1.51"	Mn-Mo	49	8
Van Dorn Iron Works	H-20542	4	1.55"	Ni-Cr-Mo	51.5	9
Standard (Great Lakes)	GSG-635	1X3	2.05"	Si-Cr-Mo-Zr	47.5	3-4
Carnegie-Illinois	15378	CB-143317	2.02"	Mn-Ni-Cr-Mo	48.5	4
Standard (Great Lakes)	GSG-635	1X4	2.03"	Si-Cr-Mo-Zr	48.5	-
Ford	92822	2040-R	1.98"	Mn-Cr-Mo	53	4-5

*Does not include the 10-20% intercritical ferrite present in bar.

2

TABLE IV

Jominy Hardenability of the Shilo Cold Test Rolled Plates

[illegible]ickness	Type Chemistry	Hardness 1/16" from Quenched End - Rc	No. of 1/16" From Quenched End at Which High or Intermediate Temperature Transformation Begins	No. of 1/16" from Quenched End at Which Abrupt Hardness Drop Begins (See Graphs of Figures 19 to 35)	No. of 1/16" from Quenched End at Which Structure Is only 90% Martensite	No. of 1/16" from Quenched End to Rc 43	F[illegible] T[illegible] fo[illegible] F[illegible] Ot[illegible] Ma[illegible]
			JOMINY BAR DATA				
				1" PLATES			
[illegible].02"	Ni-Mo	45.5	4*	3	5*	3	
[illegible].00"	Ni-Cr-Mo	48.5	3	5	5-6	6	
[illegible].02"	Ni-Cr-Mo	49	4	7	8-9	16	o[illegible]
1.00	Ni-Cr-Mo	50.5	8	20	19	28	
				1½" PLATES			
1.51"	Mn-Ni-Cr-Mo	45.5	4	5	5-6	5-6	[illegible]
[illegible].51"	Ni-Mo	44	4*	3	5*	2	
1.51"	Si-Cr-Mo-Zr	48	4	4	5-6	6	
[illegible].50"	Si-Cr-Mo-Zr	48.5	-	5	-	6-7	
1.48"	Ni-Cr-Mo	4[illegible]	3	5	5	6	1[illegible]
1.50"	Ni-Mo	[illegible].5	-	4	-	2	
[illegible].51"	Mn-Mo	50.5	11	24	20	>40	a
1.51"	Mn-Mo	4[illegible]	8	22	19	40	
1.55"	Ni-Cr-Mo	51.5	9	24	21	>40	a
				2" PLATES			
[illegible].05"	Si-Cr-Mo-Zr	47.5	3-4	5	6	7	1[illegible]
[illegible].02"	Mn-Ni-Cr-Mo	48.5	4	7	8	9	1[illegible] o
[illegible].03"	Si-Cr-Mo-Zr	48.5	-	5	-	8	
[illegible].08"	Mn-Cr-Mo	53	4-5	8	8-9	11	1[illegible] o

[illegible]rcritical ferrite present in bar.

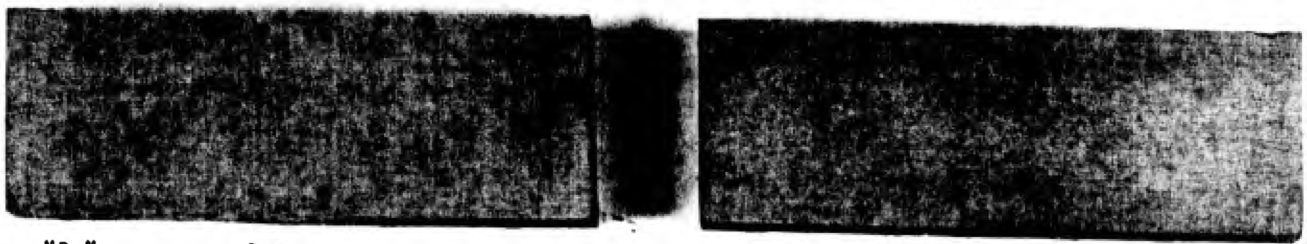
Table IV.

Rolled Plates

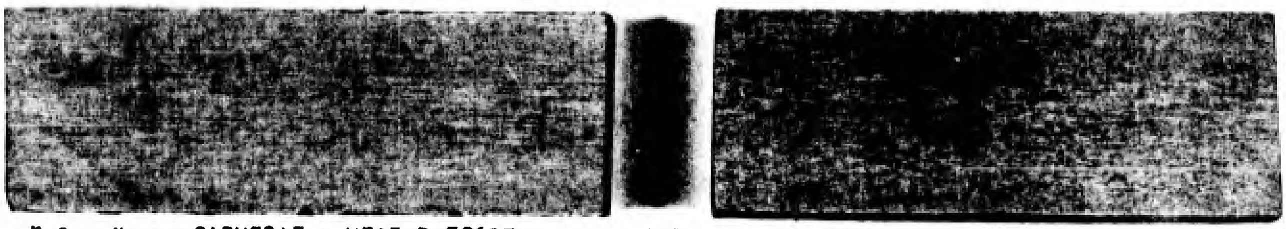
of 1/16" Quenched to Rc 43	Percent Transformation Products Other than Martensite at Rc 43	Equivalent Plate Thickness: Hardenability Criterion Is Hardness at Beginning of Drop in Jominy Curve — Still Water (H=1)^Δ	Water Spray (H=1.?)^Δ	Hardenability Criterion Is Rc 43 — Still Water (H=1)^Δ	Water Spray (H=1.?)^Δ	Adequateness of Hardenability (Ability of the Plate to Be Quench Hardened to >90% Martensite at Center of Section - From Jominy Curve and Microscopic Examination) — Still Water	Water Spray
3	0%*	<10/16"	10/16"	<10/16"	10/16"	Inadequate	Inadequate
[illegible]	20%	12/16"	1"	15/16"	1-3/16"	Inadequate	Adequate
[illegible]	30-40% in bands of 50-70%	1-2/16"	1-5/16"	2-7/16"	2-13/16"	Adequate	Adequate
[illegible]	30%	2-14/16"	3-5/16"	3-10/16"	4"	Adequate	Adequate
5-6	10% in bands of 40%	12/16"	1"	14/16"	1-1/16"	Inadequate	Inadequate
[illegible]	0%*	<10/16"	10/16"	<7/16"	7/16"	Inadequate	Inadequate
[illegible]	15%	10/16"	13/16"	15/16"	1-3/16"	Inadequate	Inadequate
[illegible]	-	12/16"	1"	1"	1-4/16"	Inadequate	Inadequate
6	25% in bands of 50%	12/16"	1"	15/16"	1-3/16"	Inadequate	Inadequate
[illegible]	-	10/16"	13/16"	<7/16"	7/16"	Inadequate	Inadequate
>[illegible]	at 40/16, 75% (Rc 44.5)	3-4/16"	3-11/16"	>3-13/16"	>3-13/16"	Adequate	Adequate
40	70-80%	3-1/16"	3-8/16"	>3-13/16"	>3-13/16"	Adequate	Adequate
>[illegible]	at 40/16, 40% (Rc 47.5)	3-4/16"	3-11/16"	>3-13/16"	>3-13/16"	Adequate	Adequate
7	15% in bands of 30%	12/16"	1"	1-2/16"	1-5/16"	Inadequate	Inadequate
[illegible]	20% in bands of 40-50%	1-2/16"	1-5/16"	1-7/16"	1-12/16"	Inadequate	Inadequate
[illegible]	-	12/16"	1"	1-4/16"	1-8/16"	Inadequate	Inadequate
[illegible]	20-30% in bands of 50-60%	1-4/16"	1-8/16"	1-12/16"	2-2/16"	Inadequate	Inadequate

ΔH is the Grossmann quenching efficiency factor.

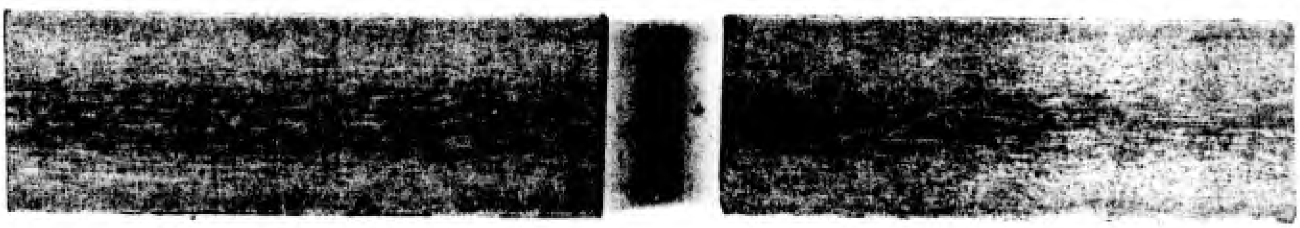
LONGITUDINAL TRANSVERSE



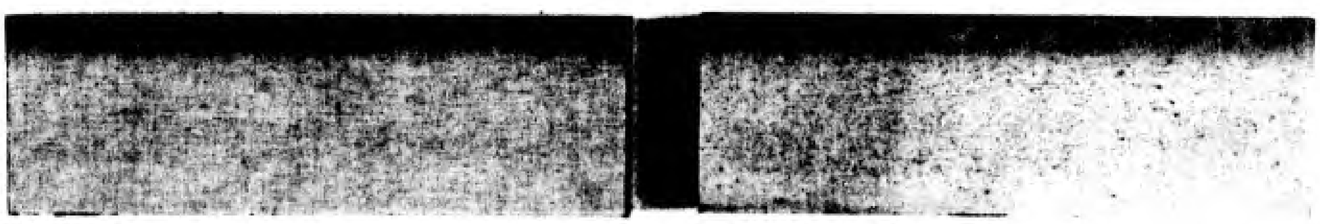
"B-" DISSTON - HEAT 3339 - PLATE I - FAILED SHOCK - NO PTP TEST "C-"



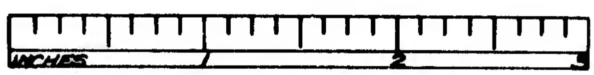
"B-" CARNEGIE - HEAT B-52607 - PLATE 4-2-T-4 - PASSED SHOCK - FAILED PTP "B-"



"B-" VAN DORN - HEAT H-40297 - PLATE I - PASSED SHOCK - FAILED PTP "C"



"B" AMERICAN CAR - HEAT H-50196 - PLATE 1702-7 - NO SHOCK TEST - FAILED PTP "B-"



ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

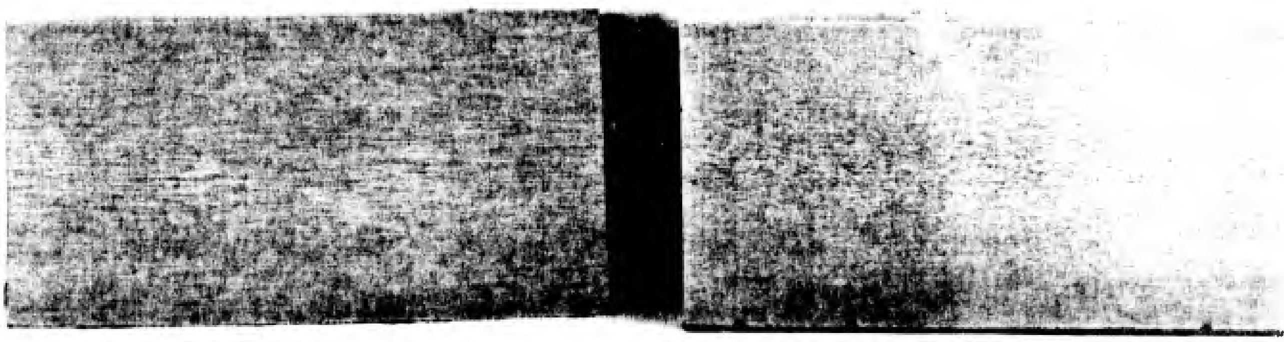
MACROETCHED SECTIONS OF 1" ROLLED ARMOR PLATE TESTED AT LOW TEMPERATURE AT CAMP SHILO, MANITOBA, CANADA. WTN.710-2205

LETTERS UNDER THE PHOTOMACROGRAPHS ARE THE RATINGS OF THE CORRESPONDING STEEL SOUNDNESS FRACTURE TEST SPECIMENS

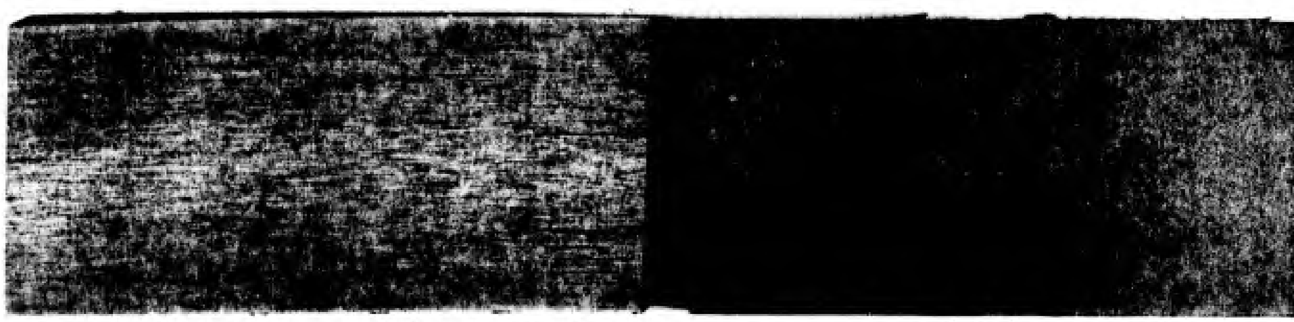
FIGURE 1

LONGITUDINAL TRANSVERSE

" C – " ARNEGIE – HEAT 22345 – PLATE 129438-CTB – FAILED SHOCK – NO PTP TEST " D "



" B " DISSTON – HEAT 22851 – PLATE 2 – FAILED SHOCK – NO PTP TEST " B "



" E " STANDARD (GREAT LAKES) – HEAT GSC-724 – PLATE 1X4 – FAILED SHOCK NO PTP TEST " E "

INCHES 1 2 3

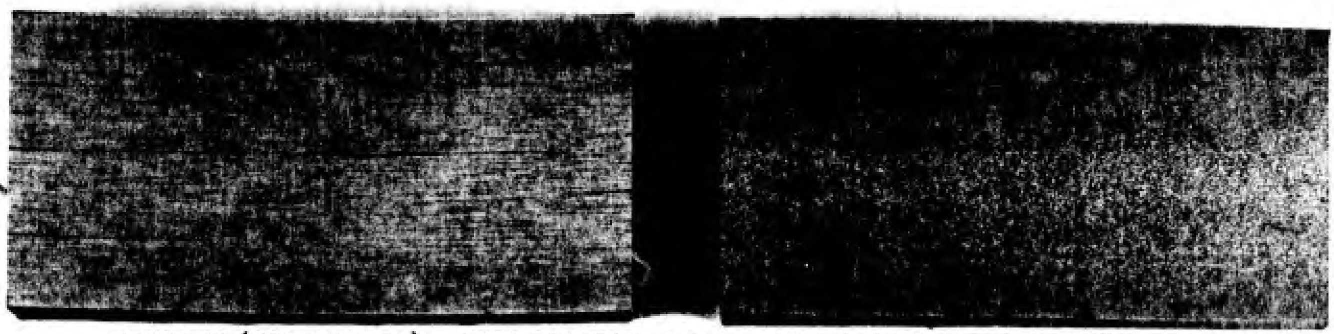
ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

MACROETCHED SECTIONS OF 1½" ROLLED HOMOGENEOUS ARMOR PLATE TESTED AT LOW TEMPERATURE AT CAMP SHILO, MANITOBA, CANADA. WTN.710-2201

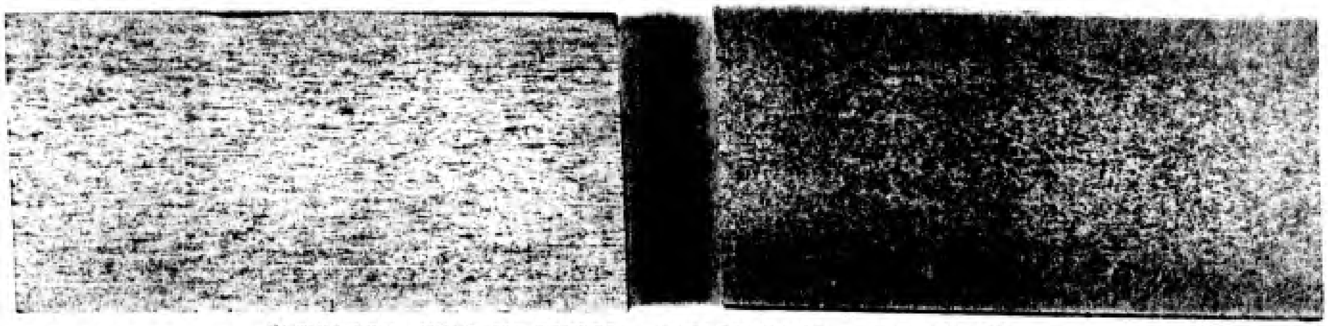
LETTERS UNDER THE PHOTOMACROGRAPHS ARE THE RATINGS OF THE CORRESPONDING STEEL SOUNDNESS FRACTURE TEST SPECIMENS.

FIGURE 2

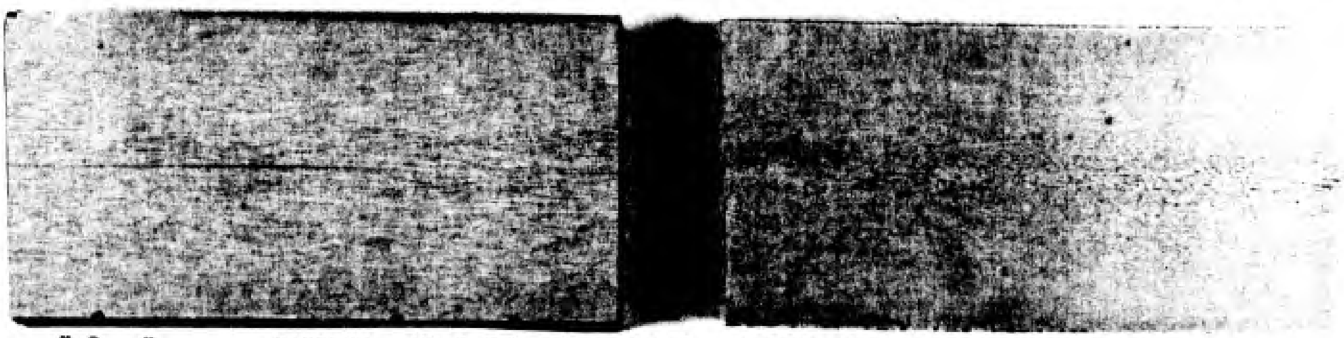
LONGITUDINAL TRANSVERSE



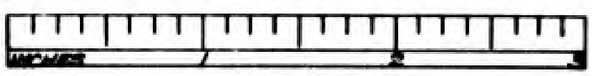
" E " STANDARD (GREAT LAKES) – HEAT GSG-724 – PLATE 1X5 – FAILED SHOCK – NO PTP TEST " E "



" C – " REPUBLIC – HEAT RH-50307G – PASSED SHOCK – FAILED PTP " D "



" B – " DISSTON – HEAT 22851 – PLATE 5 – PASSED SHOCK – PASSED PTP " B "



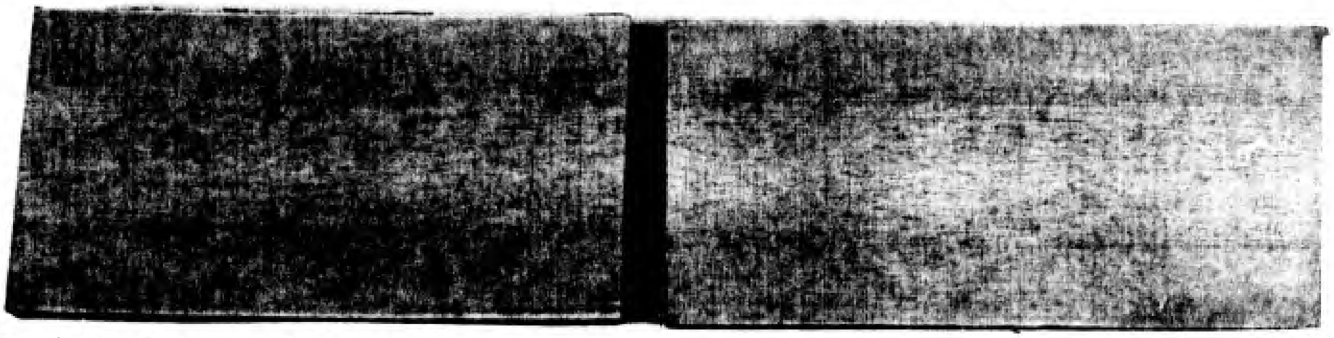
ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

MACROETCHED SECTIONS OF $1\frac{1}{2}$" ROLLED HOMOGENEOUS ARMOR PLATE TESTED AT LOW TEMPERATURE AT CAMP SHILO, MANITOBA, CANADA. WTN.710-2200

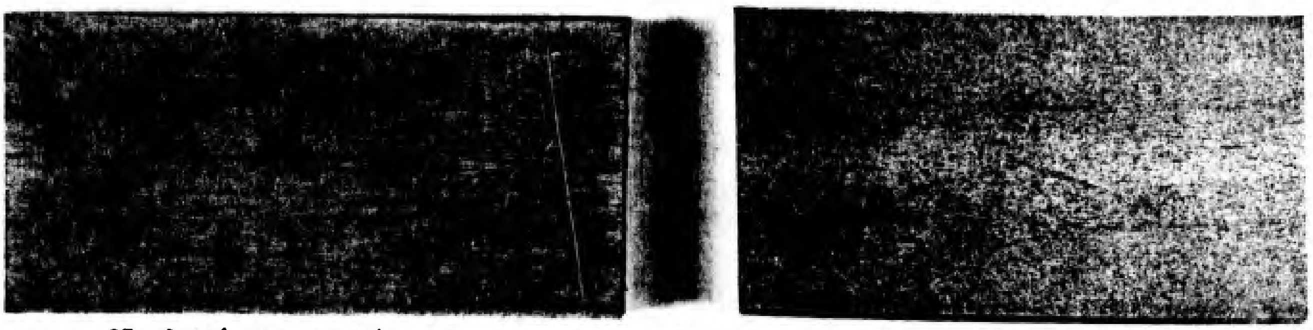
LETTERS UNDER THE PHOTOMACROGRAPHS ARE THE RATINGS OF THE CORRESPONDING STEEL SOUNDNESS FRACTURE TEST SPECIMENS.

FIGURE 3

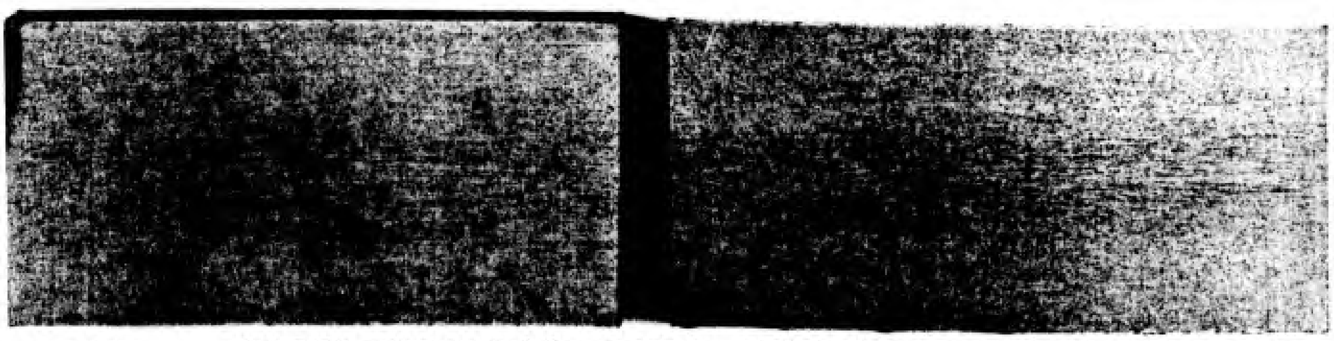
LONGITUDINAL TRANSVERSE



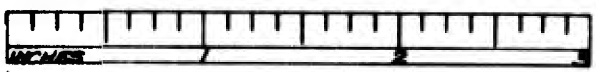
" B – " STANDARD (JONES & LAUGHLIN) – HEAT QSJ–335 – PLATE MIX3 – PASSED SHOCK – PASSED PTP " B –



" D " STANDARD(YOUNGSTOWN) – HEAT QSY–75–10 – PLATE IX5 – PASSED SHOCK – PASSED PTP " C "



" D " VAN DORN – HEAT H–20542 – PLATE 4 – PASSED SHOCK – PASSED PTP " D "



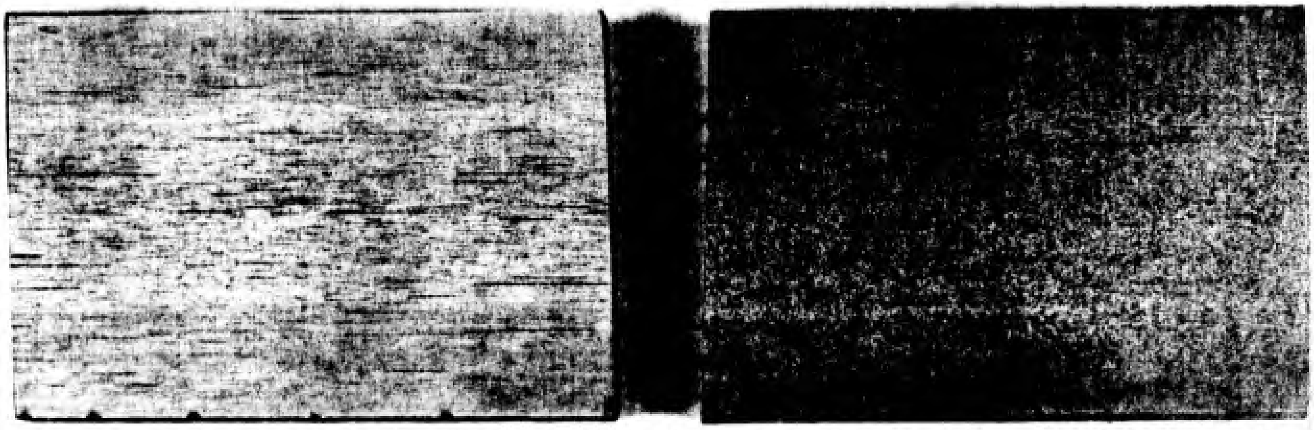
ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

MACROETCHED SECTIONS OF $1\frac{1}{2}$" ROLLED HOMOGENEOUS ARMOR PLATE TESTED AT LOW TEMPERATURE AT CAMP SHILO, MANITOBA, CANADA. WTN.710–2204

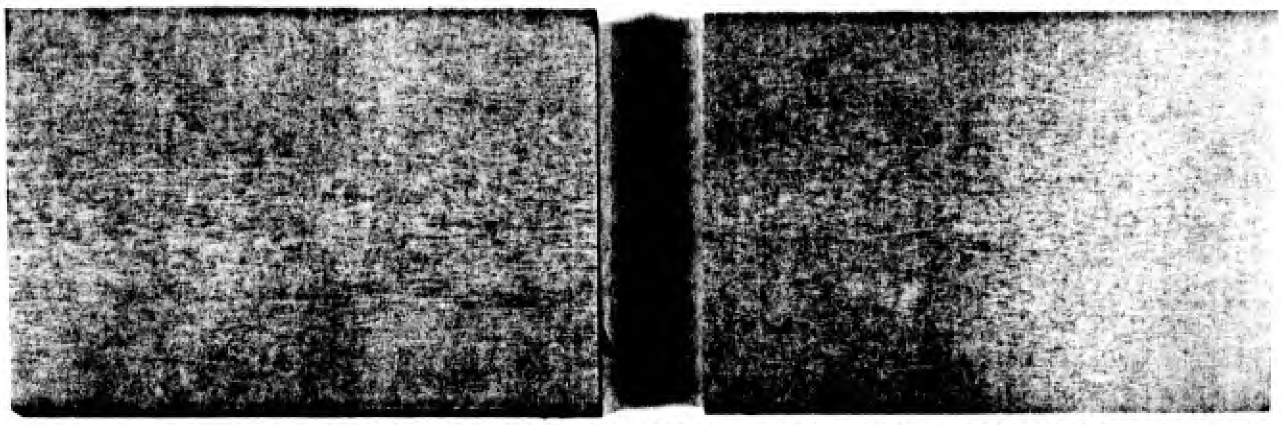
LETTERS UNDER THE PHOTOMACROGRAPHS ARE THE RATINGS OF THE CORRESPONDING STEEL SOUNDNESS FRACTURE TEST SPECIMENS.

FIGURE 4

LONGITUDINAL   TRANSVERSE



"E" STANDARD (GREAT LAKES) – HEAT GSG-635 – PLATE IXI – FAILED SHOCK – FAILED PTP "E"



"B" CARNEGIE – HEAT 15378 – PLATE TB-143317 – PASSED SHOCK – FAILED PTP "B"

INCHES 1 2 3

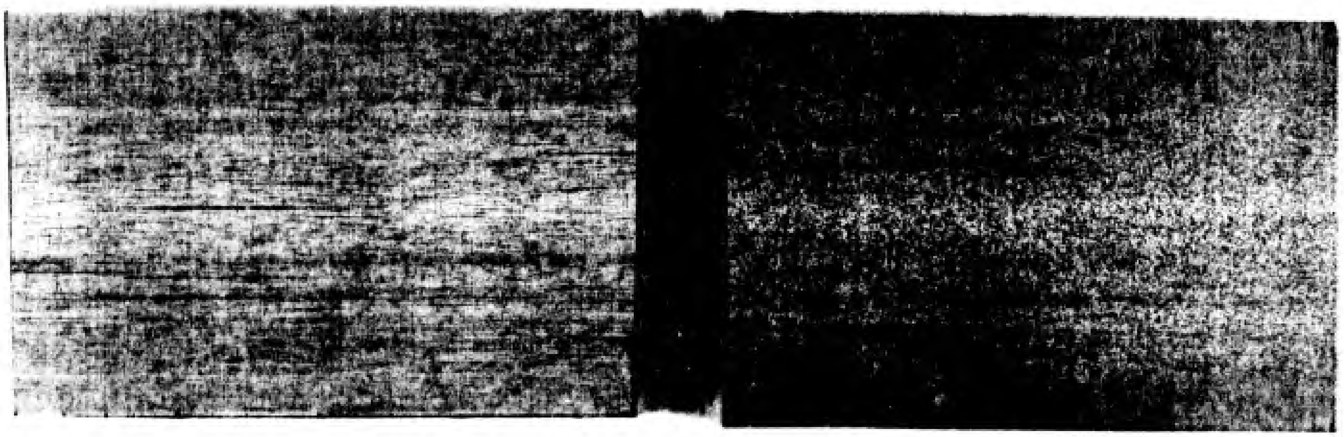
ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

MACROETCHED SECTIONS OF 2" ROLLED HOMOGENEOUS ARMOR PLATE TESTED AT LOW TEMPERATURE AT CAMP SHILO, MANITOBA, CANADA. WTN.710-2203

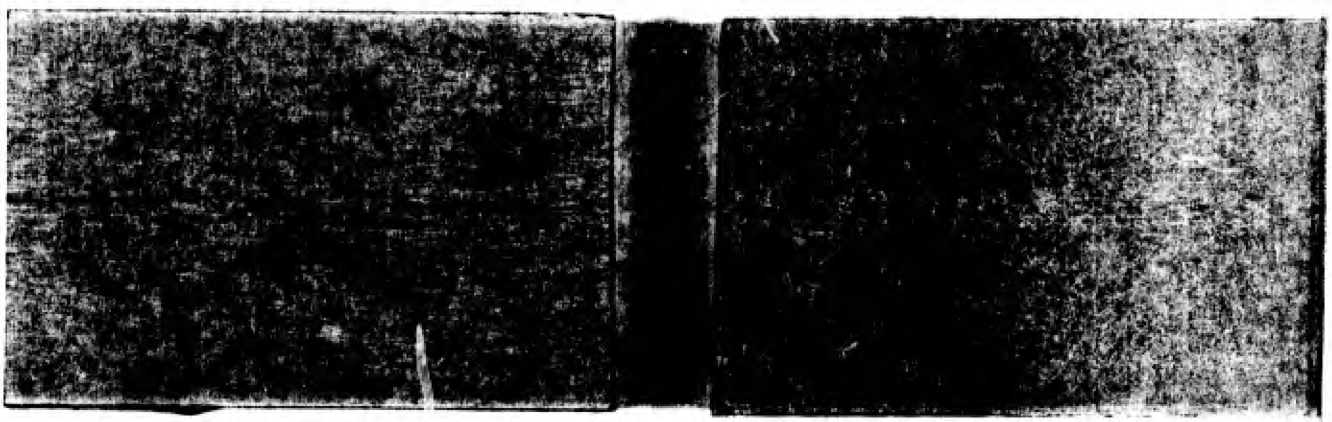
LETTERS UNDER THE PHOTOMACROGRAPHS ARE THE RATINGS OF THE CORRESPONDING STEEL SOUNDNESS FRACTURE TEST SPECIMENS.

FIGURE 5

LONGITUDINAL TRANSVERSE



"E" STANDARD (GREAT LAKES) – HEAT GSG–635 – PLATE 1X4 – PASSED SHOCK – FAILED PTP "E"



"D" FORD – HEAT 9282E – PLATE 2040-R – PASSED SHOCK – PASSED PTP "D"

ORDNANCE DEPT. U.S.A.
WATERTOWN ARSENAL

MACROETCHED SECTIONS OF 2" ROLLED HOMOGENEOUS ARMOR PLATE TESTED AT LOW TEMPERATURE AT CAMP SHILO, MANITOBA, CANADA. WTN.710–2202

LETTERS UNDER THE PHOTOMACROGRAPHS ARE THE RATINGS OF THE CORRESPONDING STEEL SOUNDNESS FRACTURE TEST SPECIMENS.

FIGURE 6

Typical Nonmetallic Inclusions in the 1" Plates
(Unetched longitudinal specimens photographed at X100)

Disston Plate 1
Silicates in moderate quantity and mainly randomly distributed.

Carnegie Plate 4-2-T-4
Moderate amount of inclusions. No long stringers.

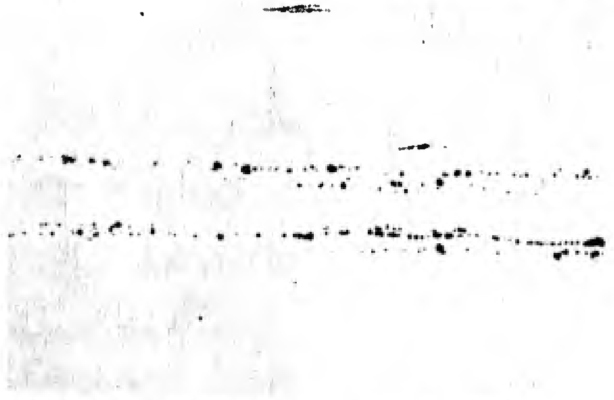
Van Dorn Plate 1
Thin elongated inclusions in concentrations at center of section.

American Car Plate 1702-7
Small amount of inclusions. No long stringers.

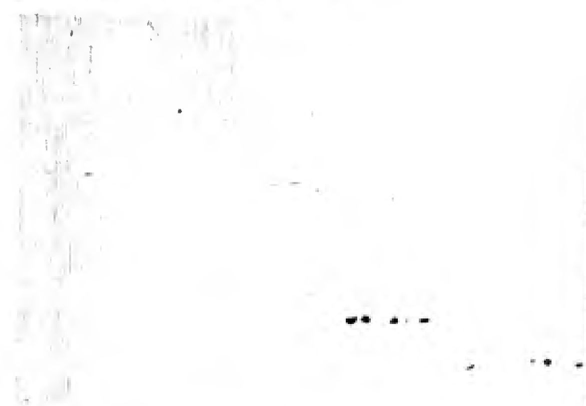
WTN.639-6805

FIGURE 7

Typical Nonmetallic Inclusions in the 1½" Plates
(Unetched longitudinal specimens photographed at X100)



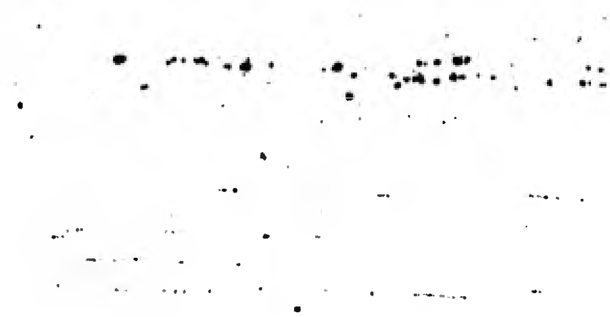
Carnegie Plate 129438-CTB
Oxides in many long stringers throughout the section.



Disston Plate 2
Small amount of inclusions. No long stringers.

Great Lakes Plate 1X4
Oxides in many long stringers throughout the section.

Great Lakes Plate 1X5
Oxides in many long stringers throughout the section.

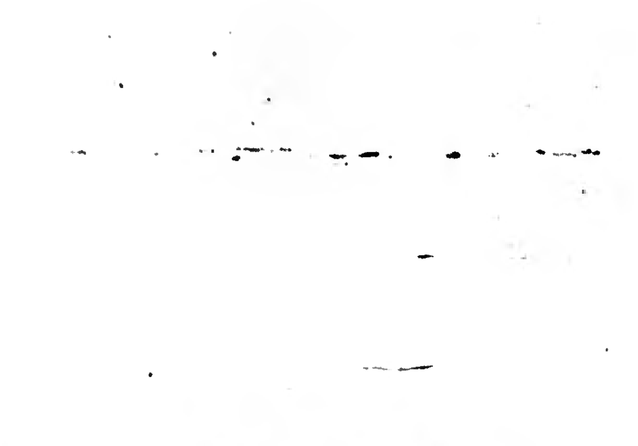


Republic Heat RH-50307G
Throughout the section - Great quantity of ... in elongated inclusions in stringers and moderate amount of long oxide stringers.

WTN.639-6806

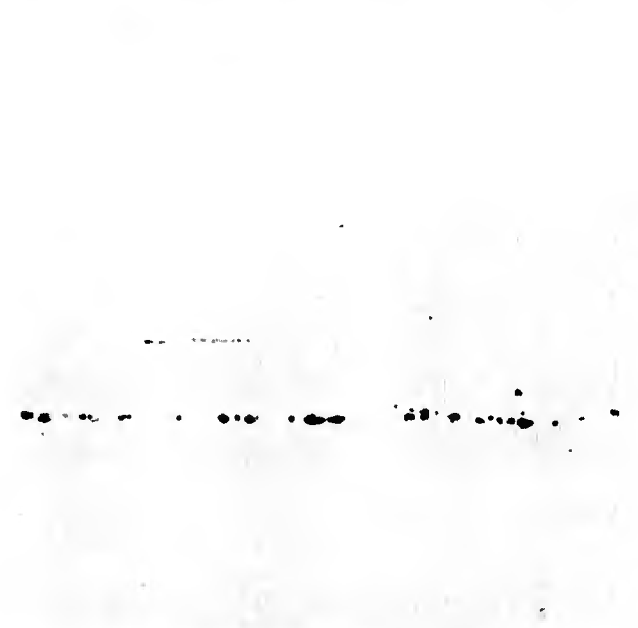
FIGURE 8

Typical Nonmetallic Inclusions in the 1½" Plates
(Unetched longitudinal specimens photographed at X100)



Disston Plate 5
Center of section - Moderate quantity of inclusions. Length of stringers is not great.

Jones and Laughlin Plate M1X3
Large number of inclusions. No long stringers.



Youngstown Plate 1X5
Oxides in many long stringers, mainly at center of section.

Van Dorn Plate 4
Thin elongated inclusions in concentrations mainly at center of section.

WTN.639-6807

FIGURE 9

Typical Nonmetallic Inclusions in the 2" Plates
(Unetched longitudinal specimens photographed at X100)

Great Lakes Plate 1X1
Oxides in many long stringers throughout the section.

Carnegie Plate TB-143317
Small amount of sulphides. No long stringers.

Great Lakes Plate 1X4
Oxides in many long stringers throughout the section.

Ford Plate 2040-R
Sulphides in concentrations mainly at center of section.

FIGURE 10

WTN.639-6808

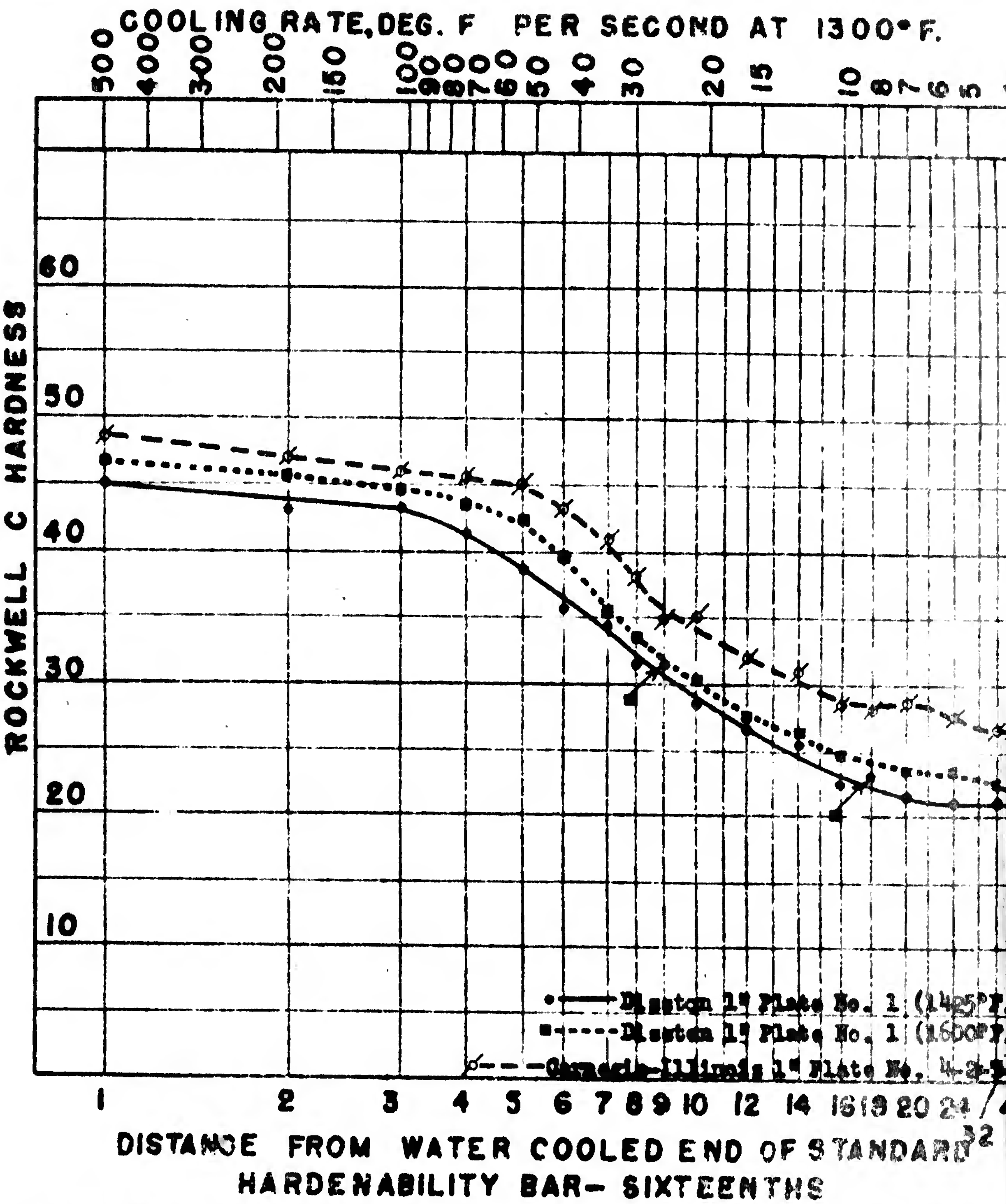


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	QUENCH TEMP	TIME	G.S
1	3339	.22	.51	.25	.018	.017	2.50	.21	.32	.13	.01	1425°F	1 hr.	
1	3339	.22	.51	.25	.018	.017	2.50	.21	.32	.13	.01	1600°F	1 hr.	
					DISSTON 1" PLATE									
4-2-T-4	B-82607	.26	.95	.24	.026	.016	1.04	.45	.39	.03	.02	1550°F	1 hr.	
					Carnegie-Illinois 1" Plate									

FIGURE

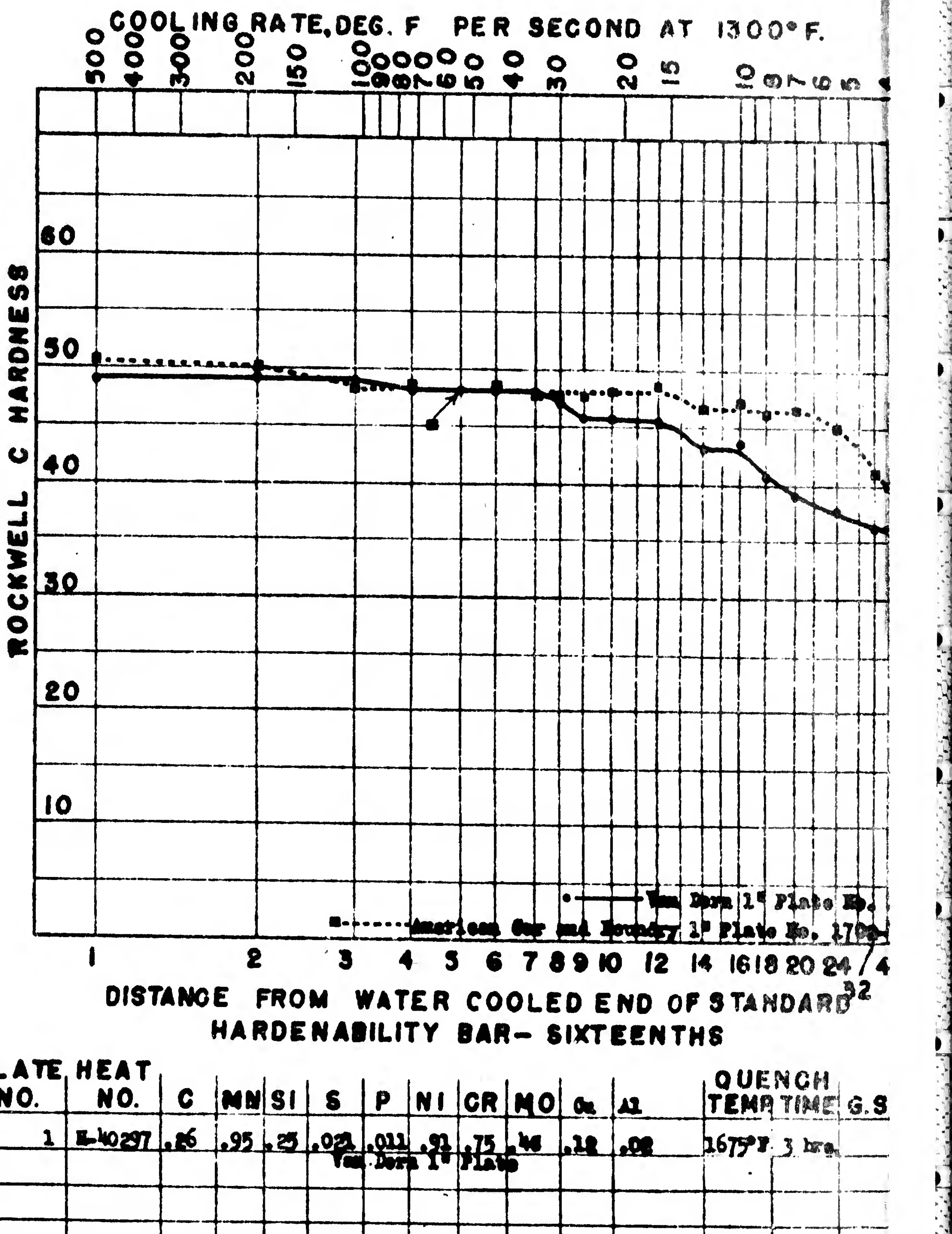


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	QUENCH TEMP	QUENCH TIME	G.S
1	H-40297	.26	.95	.25	.021	.011	.91	.75	.46	.12	.02	1675°F	3 hrs.	
					Van Dorn 1" Plate									
1702-7	H-50196	.27	.45	.21	.018	.010	3.41	.40	.37			1460°F	1-1/4 hrs.	
				American Car and Foundry 1" Plate										

FIGURE 1

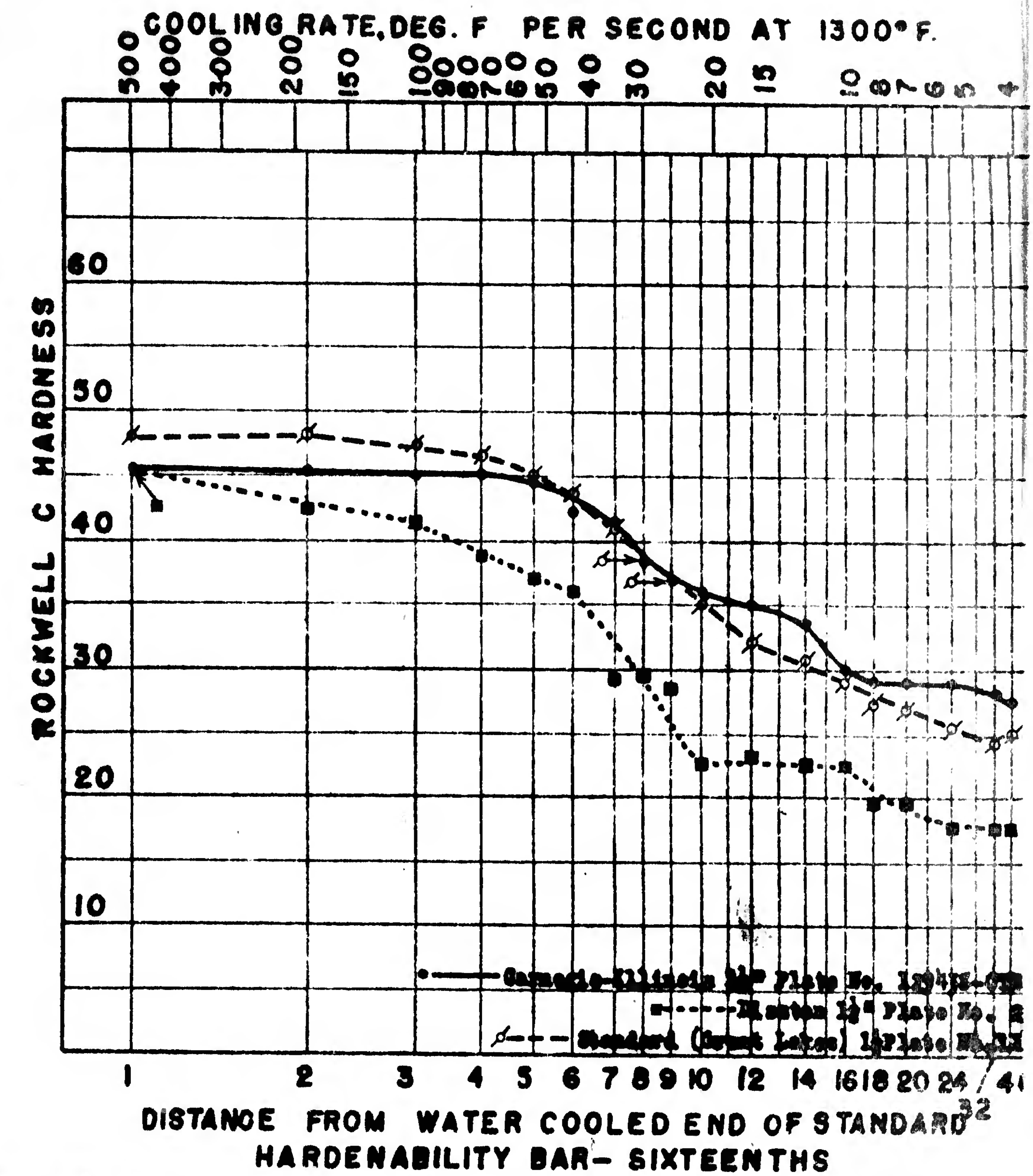


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al Zr	QUENCH TEMP	TIME	G.S.
129438-[illegible]	22345	.25	1.05	.27	.025	.014	.93	.62	.36	.06	.03	1550°F	1 hr.	
Carnegie-Illinois 1½" Plate														
2	22851	.19	.4[illegible]	.27	.022	.013	3.05	.04	.30	.14	.01	1425°F	2hrs.	
Disston 1½" Plate														
1[illegible]	080-724	.2[illegible]	.[illegible]	.63	.022	.0[illegible]	—	.61	.15	.10	.015 .085	1600°F	2-3/4 hrs.	
Standard (Great Lakes) 1½" Plate														

FIGURE 13

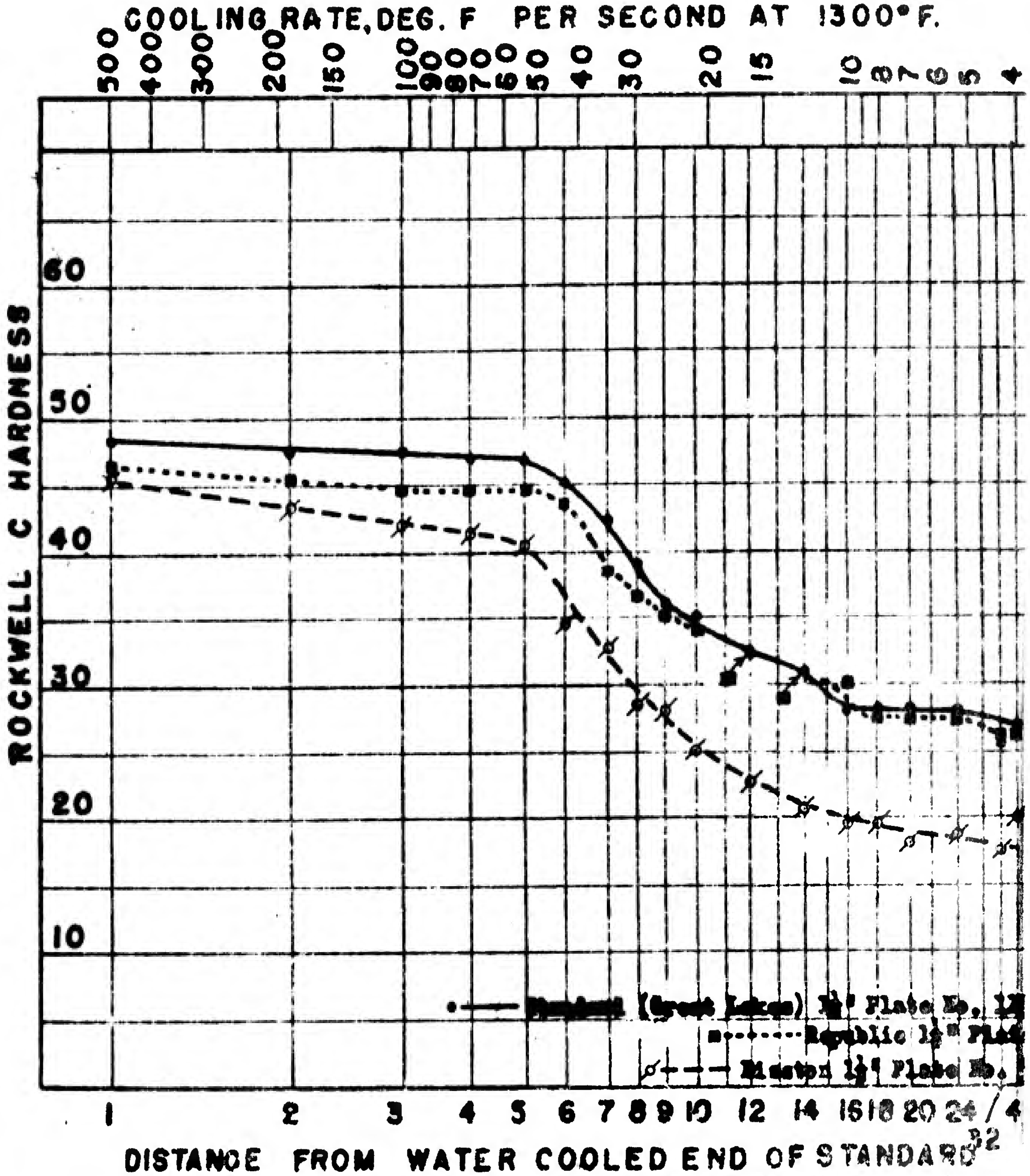


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	Zr	QUENCH TEMP.	TIME	G.S.
125	080-724	.28	.90	.63	.022	.022	-	.62	.15	.10	.015	.11	1600°F	2-3/4 hrs.	
Standard (Great Lakes) 1½" Plate															
-	[illegible]-50307[illegible]	.27	.88	.27	.020	.014	.80	.73	.41	.12	.02		1600°F	2-3/4 hrs.	
Republic 1½" Plate															
5	28851	.20	.51	.28	.021	.013	3.09	.04	.29	.14	.01		1425°F	2 hrs.	
Disston 1½" Plate															

FIGURE

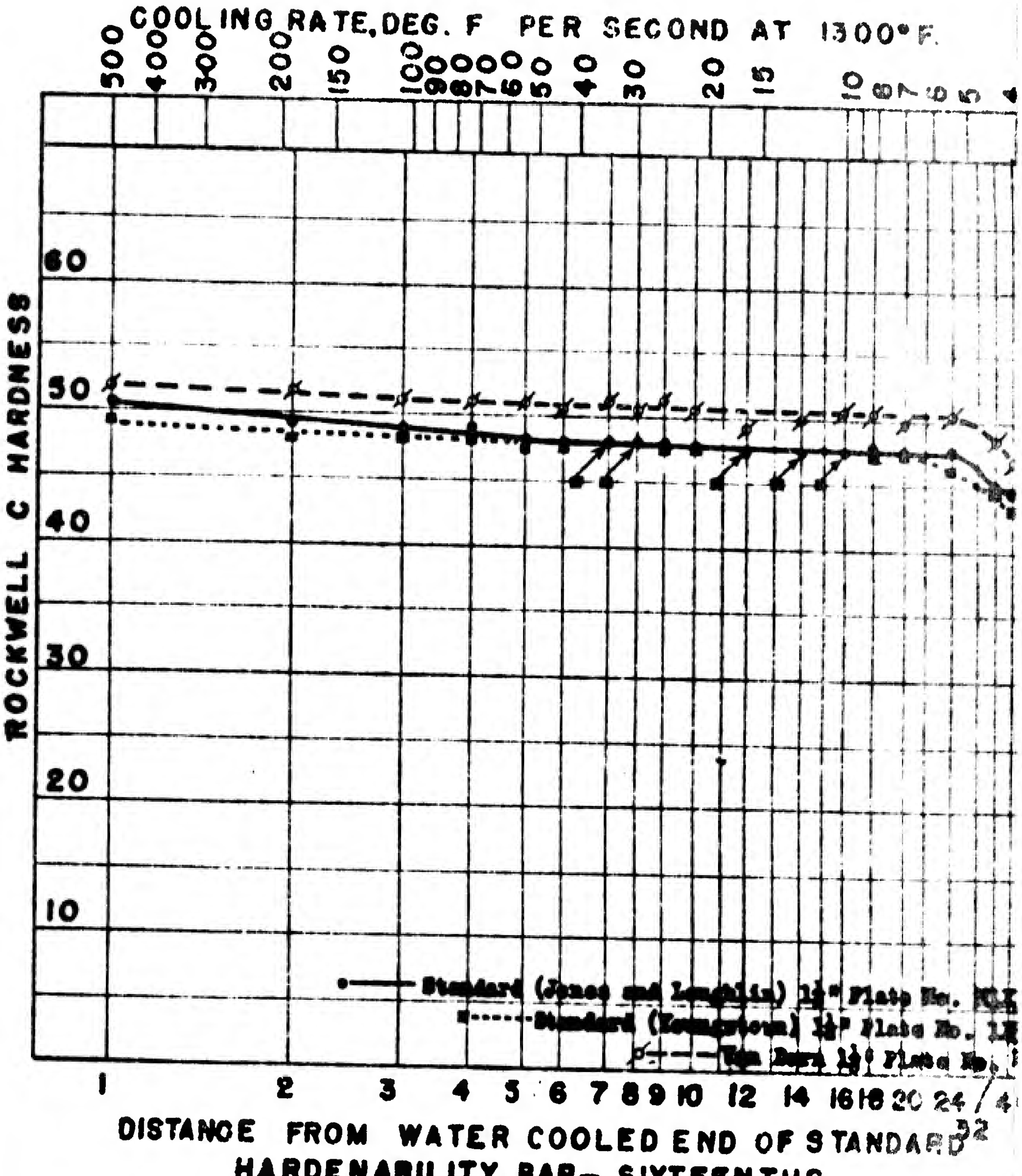


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	B	QUENCH TEMP	TIME	G.S.
MLX3	08J-335	.27	1.5[illegible]	.25	.019	.017	-	.02	.41	.01	.04	.0009	1600°F	2-3/4 hrs.	
Standard (Jones and Laughlin) 1½" Plate															
1L5	[illegible]-75-10	.29	1.65	.21	.020	.037	.09	.02	.37	.06	.03		1600°F	2-3/4 hrs.	
Standard (Youngstown) 1½" Plate															
4	E-20542	.30	.93	.26	.019	.021	1.22	1.03	.61	.12	.02		1675°F	3 hrs.	
Van Dorn 1½" Plate															

FIGURE 1

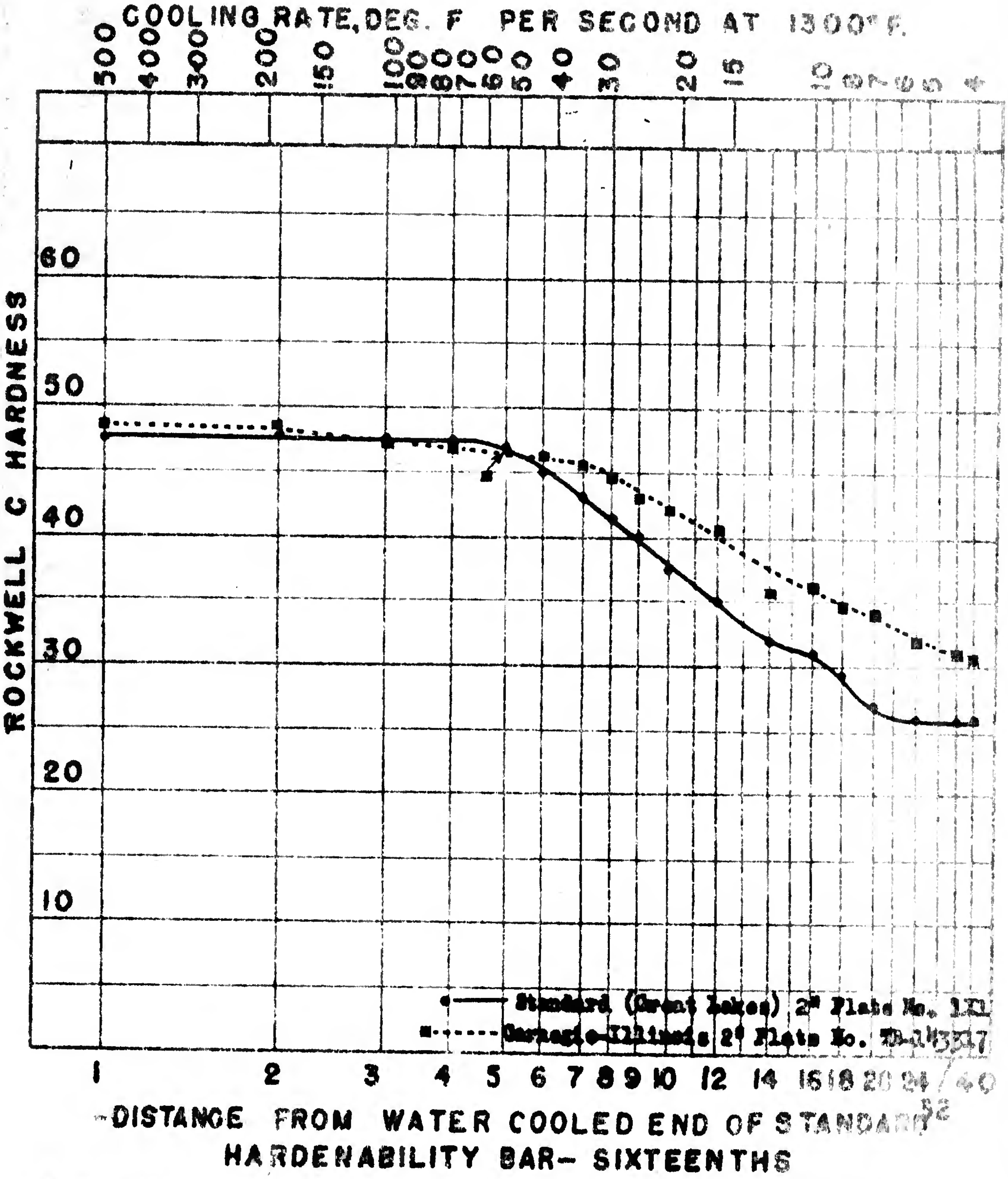


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	Zr	QUENCH TEMP	TIME	G.S.
1X1	080-635	.29	.85	.75	.022	.014	—	.60	.16	.08	.015	.05	1600°F	3-1/4 hrs.	
Standard (Great Lakes) 2" Plate															
TB-143X17	15378	.26	1.06	.23	.024	.014	1.02	.57	.34	.06	.03		1550°F	1 hr.	
Carnegie-Illinois 2" Plate															

FIGURE 16

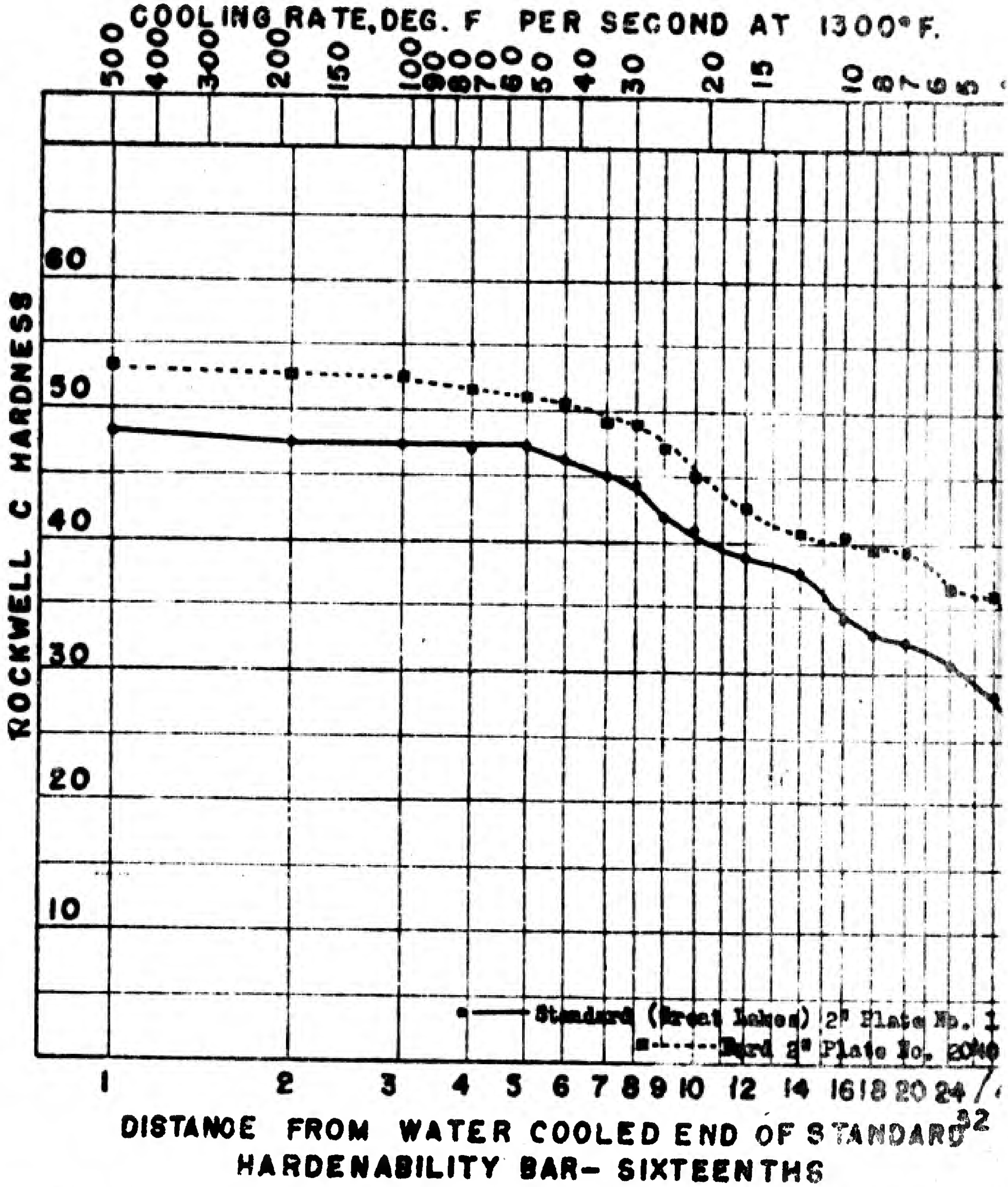
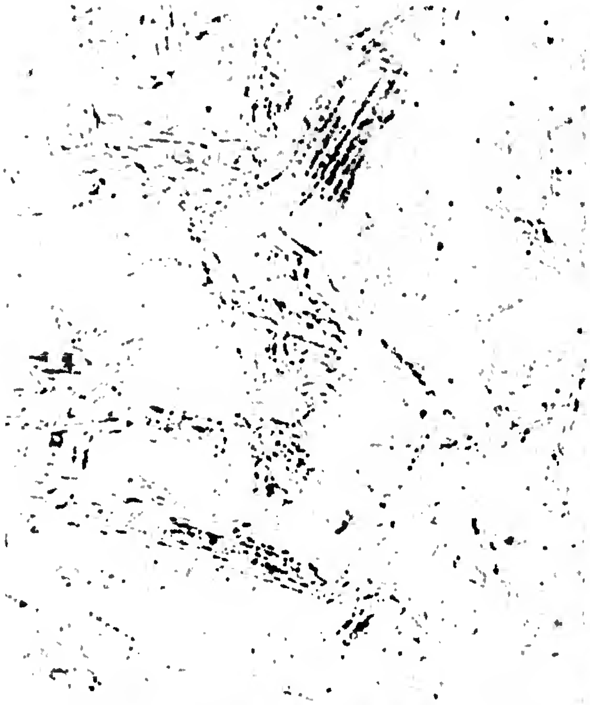


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	Zr	QUENCH TEMP	TIME	G.S
1X4	030-635	.28	.85	.75	.021	.014	-	.58	.17	.09	.005	.105	1600°F	3-1/4 hrs.	
				Standard (Great Lakes) 2" Plate											
2040-R	92523	.30	1.37	.25	.026	.020	.10	.60	.41	.16	.02		1675°F	4 hrs.	
						[illegible] 2" PLATE									

FIGURE

Microstructures at Rc 43 in Jominy Bars of Various Hardenabilities
(All Jominy bars etched with 4% Picral and photographed at X1000).



Great Lakes 2" Plate No. 1X1
Microstructure at 7/16" from the quenched end. Amount of non-martensitic products is 15%.

Van Dorn 1" Plate No. 1
Microstructure at 16/16" from the quenched end. Amount of non-martensitic products is 30-40%.

Jones and Laughlin 1¼" Plate No. M1X3
Microstructure at 40/16" from the quenched end. Amount of non-martensitic products is 75%. (Note: In this case hardness is Rc 44.5.)

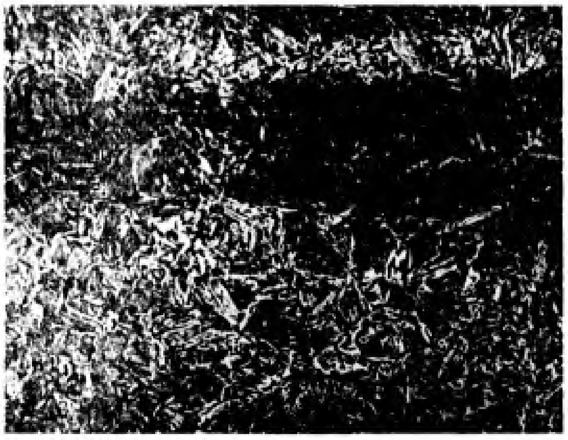
WTN.639-6809

FIGURE 18

INCLOSURE A

Data Sheets of the 17 Plates
Examined and Figures 19 to 35

Disston 1" Plate No. 1
(Microspecimen etched with 4% Picral)



X200 Center of Section X1000

Severe banding - The light etching bands consist of some intercritical ferrite and tempered martensite and a fairly large amount of tempered non-martensitic austenite decomposition products.

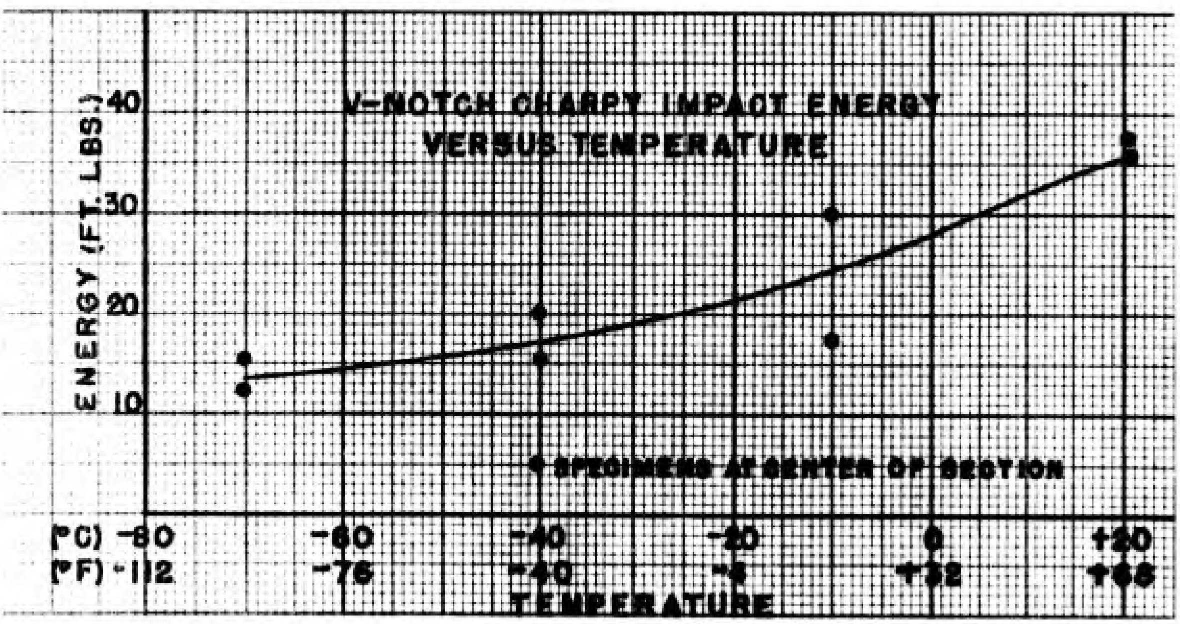


FIGURE 19

WTN.639-6810

Henry Disston and Sons, Inc.

Heat No. 3339 | Plate No. 1 | Thickness 1.02"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.23	.51	.22	.015	.020	2.45	.21	.29	-	-
Watertown Arsenal	.22	.51	.25	.018	.017	2.50	.21	.32	.13	.01

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1450	1½	2	Water Spray
1050		2	Air

Physical Properties Reported

Brinell 331-341

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-29°F.	37 mm APC M51 at 25°	1271(+5)	Failed: CP-½"x1". Punching. 2x3" B.S.	37 mm APC M51	No test.

In this heat: 3 plates of 4 failed shock. (Failed -27°F, -29°F, and -30°F (by B.S.). Passed -22°F (Pun. S.).) 0 plates of 3 failed PTP. (Passed -22°F and -27°F (no B.S.). Passed -30°F (allowable B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
316	316	302	B-	C-	Fibrous	Mixed (Trace Cryst.)	Mixed (30% Cryst.)

Macrostructure and Microscopic Inclusion Determination

Macrostructures are similar in both rolling directions. The laminations revealed by the fracture test are not shown by the macrostructure. Microscopic examination revealed only short stringers of silicates randomly distributed.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
45.5	3	3	-	10/16"	-	10/16"

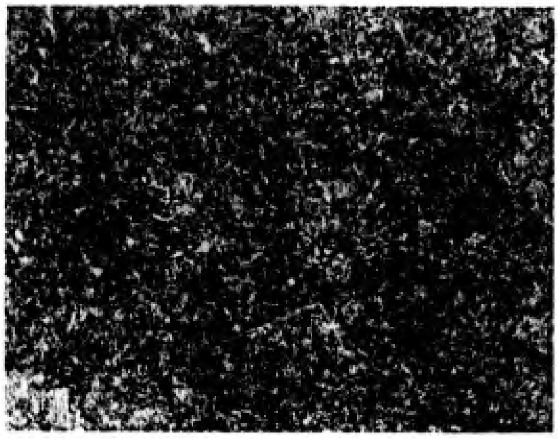
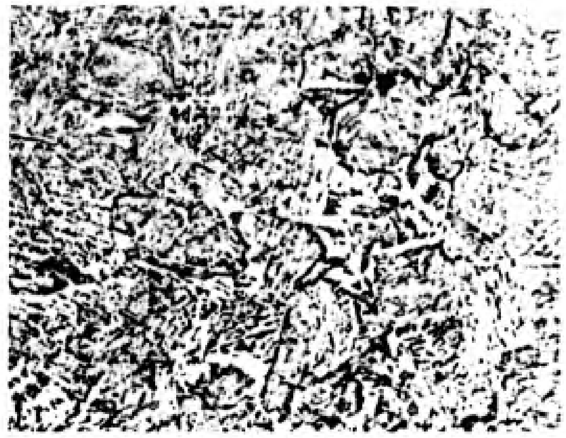
Microstructure and Remarks

In addition to some ferrite resulting from the plate having been austenitized within the critical range, a fairly large amount of austenite decomposition products other than martensite is present at the center of the section. Resulting shock properties are poor; the fracture of the material is brittle and the center of section Charpy impact energy drops rapidly with decrease of temperature from room temperature. Ballistic shock performance of this series was therefore poor.

The >90% martensite hardenability of the steel would have been borderline had the quenching temperature been 1600°F. The plate having been quenched from within the critical range, the presence of high nickel content was unable to counteract the poor shock properties imparted by the resulting structure.

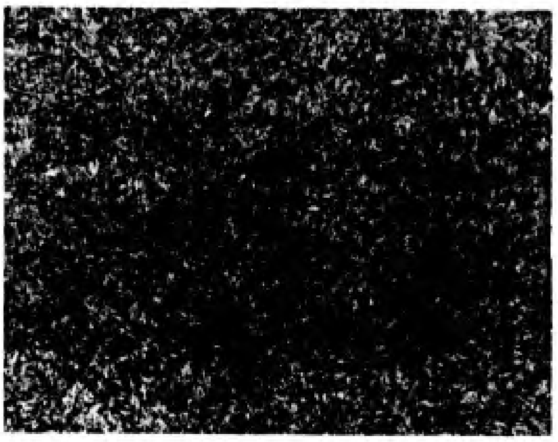
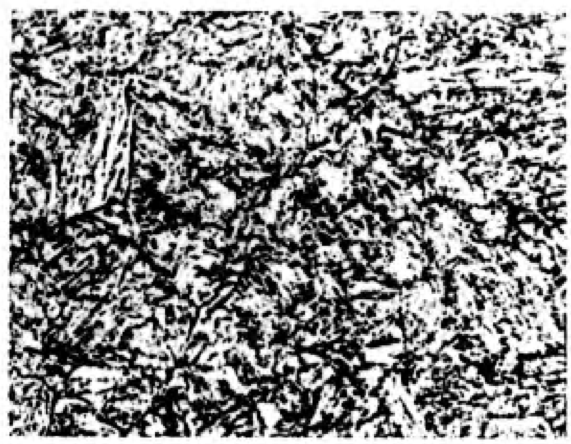
The occurrence of back spalling under PTP attack with the overmatching 37 mm shot when the testing temperature of the series was lowered to -30°F is attributed to the "C" steel quality.

Carnegie-Illinois 1" Plate No. 4-2-T-4
(Microspecimen etched with 4% Picral)

X200 **Midway Between Center and 321 Brinell Face** X1000

No banding - Microstructure consists of tempered martensite and some tempered non-martensitic austenite decomposition products.

X200 **Midway Between Center and 352 Brinell Face** X1000

No banding - Microstructure is tempered martensite with only traces of non-martensitic austenite decomposition products.

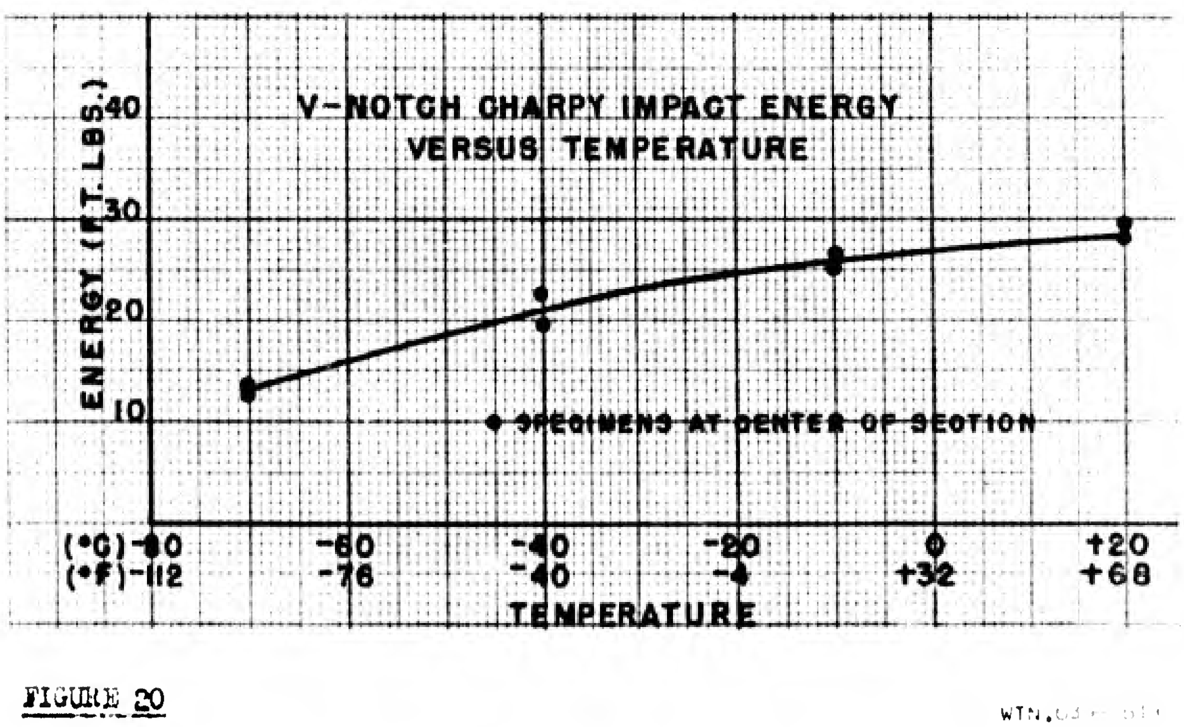


FIGURE 20

DATA SHEET NO. 2

Carnegie-Illinois Steel Corp.

Heat No. B-52607 | Plate No. 4-2-T-4 | Thickness 1.00"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.27	.91	.21	.020	.020	1.03	.40	.38	-	-
Watertown Arsenal	.26	.95	.24	.026	.016	1.04	.45	.39	.03	.02

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1544	1	3/4	Water
914	2-1/4	1	Water

Physical Properties Reported

T.S.	164,000	% R.A.	56.5
Y.P.	154,000	Izod	-
% Elong.	16.5	Brinell	332

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-27°F.	37 mm APC M51 at 25°	1252(+2)	Passed: 2" circular crack.	37 mm APC M51	Failed: Inc. B.S. 4½" diameter.

In this heat: 1 plate of 4 failed shock. (Failed -27°F (CP-B.S.). Passed -18°F (3" crack), -19°F (no cracking), and -27°F (2" crack).) 1 plate of 3 failed PTP. (Failed -27°F (inc. excessive B.S.). Passed -18°F and -19°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Trans.
321 352	One side 321 Other side 352	331	B-	B-	Fibrous	Mixed (Trace Cryst.)	Mixed (5% Cryst.)

Macrostructure and Microscopic Inclusion Determination

Macrostructures are fairly similar in both rolling directions. Both macrostructure and microscopic inclusion determination indicated that the steel is fairly clean and free from long stringers.

Jominy Hardenability

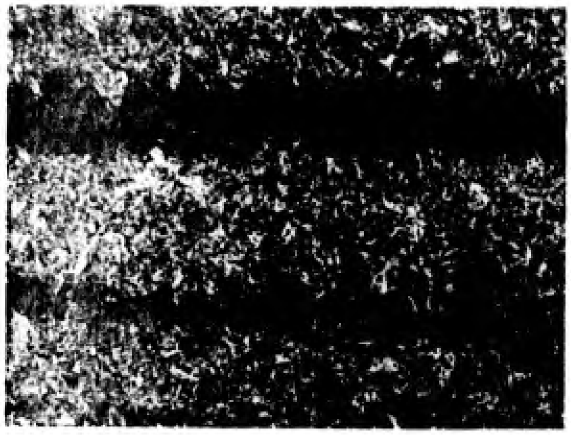
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
48.5	5	6	12/16"	1"	15/16"	1-3/16"

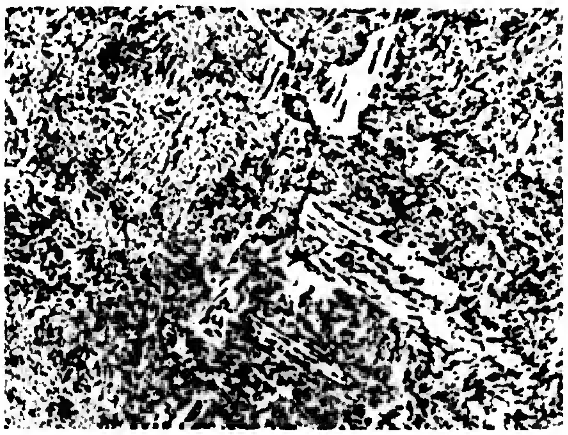
Microstructure and Remarks

The structural variations from face to face (see Fig. 20) indicate that the plate had been quenched more severely at one face than at the other. The plate was capable of being essentially completely quench hardened (>90% martensite) in water by a vigorous quench at both faces.

The fibre fracture contains only a small amount of crystallinity, but the center of section Charpy impact energy at -40°C is indicative of a transition from ductile to brittle behavior. The borderline ballistic shock behavior of this series is associated with excessive and non-uniform hardness and perhaps also the nonmartensitic transformation products in the region adjacent to the softer face. Since the material is free from long inclusion stringers, excessive hardness is also seen as the cause of PTP spalling of the plate, which was tested at the lowest temperature of the series.

Van Dorn Iron Works 1" Plate No. 1
(Microspecimen etched with 4% Picral)





X200 Center of Section X1000

Prominent banding - The light etching matrix consists of tempered martensite and some tempered non-martensitic austenite decomposition products (X1000 photo.).

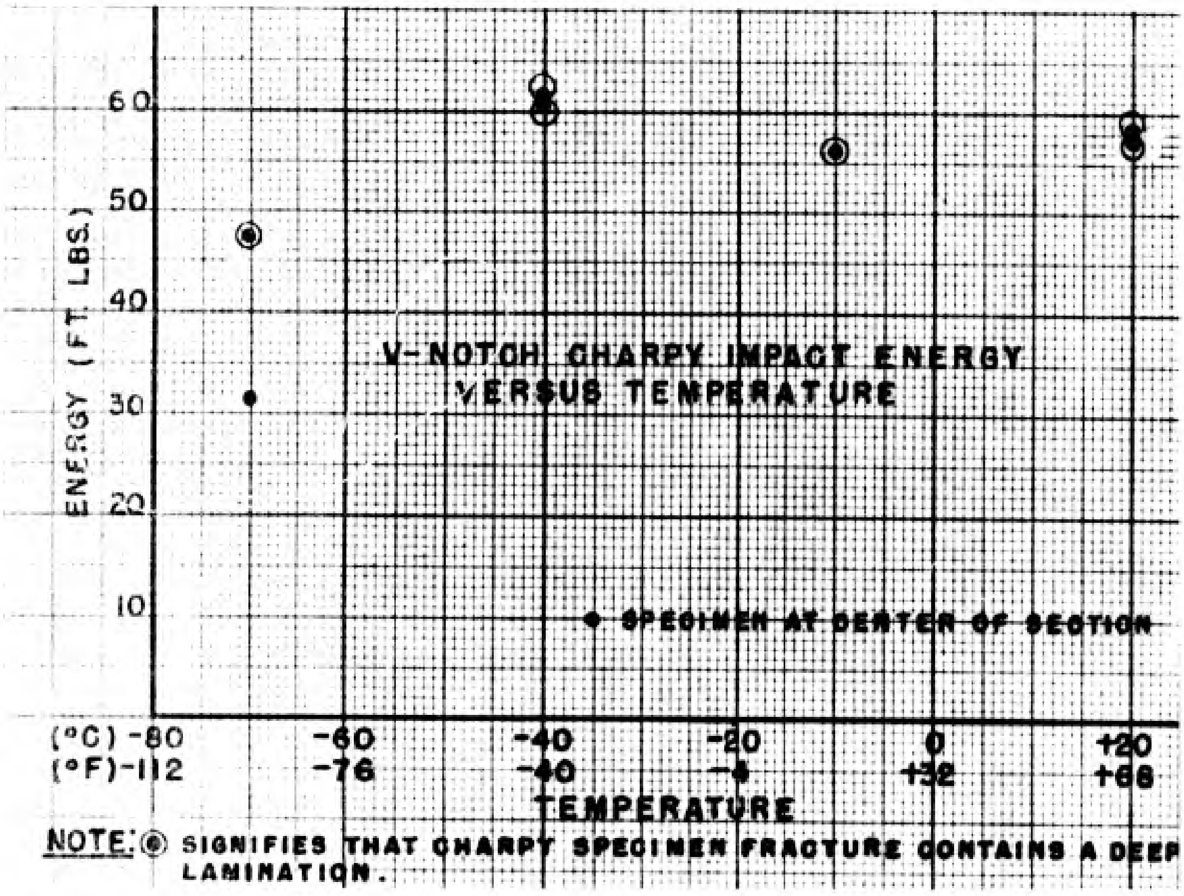


FIGURE 21

WTN.639-6812

DATA SHEET NO. 3

Van Dorn Iron Works Co.

Heat No. H-40297 | Plate No. 1 | Thickness 1.02"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.26	.92	.20	.017	.014	1.24	1.03	.62	-	-
Watertown Arsenal	.26	.95	.25	.021	.011	.91	.75	.48	.12	.02

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant

Physical Properties Reported

Brinell 287-327

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-16°F.	37 mm APC M51 at 25°	1273(+7)	Passed: No cracks.	37 mm APC M51	Passed: 2x2-1/4".
-34°F.	"	"	"	"	Failed: 3-1/4x4" w/B.S.

Note: This plate failed B.L. at +21°F and -16°F.

In this heat: 0 plates of 4 failed shock. (Passed -8.5°F and -30°F, -16° and -34°F, -31°F, and -31°F (no cracking).) 1 plate of 4 failed PTP. (Plate above. Passed -8.5°F and -30°F, -31°F, and -31°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
255	269	269	B- Centerline	C	Fibrous	Fibrous	Fibrous

Macrostructure and Microscopic Inclusion Determination

Macrostructures are similar in both rolling directions. The steel soundness test "C" rating is shown by the macrostructure to have been caused by numerous centerline stringers. Microscopic determination revealed concentrations of thin elongated inclusions at the center of the section.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
49	7	16	1-2/16"	1-5/16"	2-7/16"	2-13/16"

Microstructure and Remarks

At the center of the section some nonmartensitic austenite decomposition products are present. Nevertheless the fibre test fracture is wholly fibrous, and all plates of the series passed the ballistic shock test. A lamination is present at the center of the section in the fibre fracture, but since it is not severe, in all probability only a small amount, if any, of crystallinity would have been present had the steel been clean.

The microstructure is due either to slack quenching or quench hardening in a medium of low quenching efficiency, such as oil, for the hardenability is adequate to essentially completely quench out (>90% martensite) in still water a plate 1-2/16" thick. The impact properties cannot be judged from the Charpy data since deep laminations are present in the Charpy specimen fractures.

A "C" steel soundness fracture rating is apparently responsible for failure to pass the PTP test at the low testing temperature, -34°F.

American Car and Foundry 1" Plate No. 1702-7
(Microspecimen etched with Nital-Picral)

X200 — Center of Section — X1000

No banding - The structure resembles tempered martensite plus tempered low temperature bainite. Traces of a ferritic non-martensitic transformation product are present.

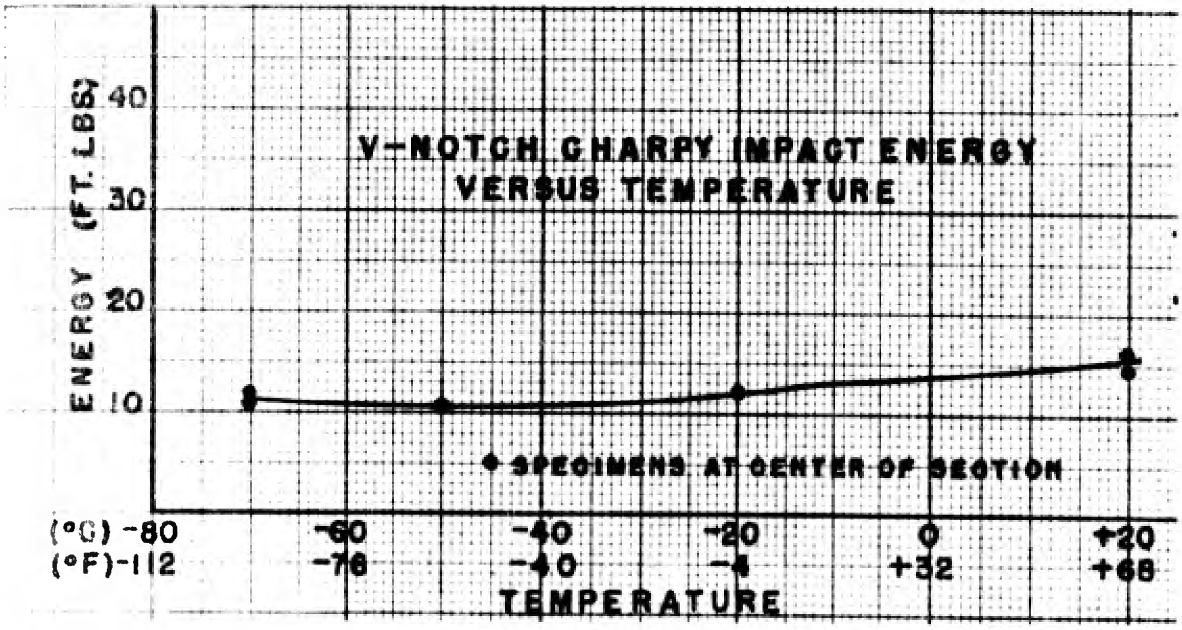


FIGURE 22

DATA SHEET NO. 4

American Car and Foundry Co.*

Heat No. H-50196 Plate No. 1702-7 Thickness 1.00"
*Carburized Plate

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo
Company	.26	.45	.18	.017	.016	3.35	.31	.35
Watertown Arsenal	.27	.48	.21	.018	.010	3.41	.40	.37

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant	Physical Properties Reported
1725	83 hrs.			
1750			Air	
1480			Interrupted Oil	Brinell 485/379
750			Air	

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
+31°F.	37 mm APC M51 at 25°		No Test	37 mm APC M51	Passed: 2-1/16x2-1/16" B.S.
+31°F.				"	Passed: 2½x2-15/16" B.S.

In this heat: 0 plates of 1 failed shock. (Passed -15°F at 1262 f/s (no cracking).) 1 plate of 3 failed PTP. (This plate failed +31°F and -15°F (excessive B.S.) and passed 31°F (allowable B.S.). Passed +31°F and +31°F (allowable B.S.) and passed +31°F (allowable B.S.).)

Hardness and Fracture Tests

BHN at Surface	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.
Case Face 514 / Core Face 401	401	B	B	Cryst.	Cryst.

Macrostructure and Microscopic Inclusion Determination

Macrostructures are similar in both rolling directions. Both macrostructure and microscopic inclusion determination indicated that the steel is clean and free from long stringers.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Water Spray (H=1.8)
50.5	20	28	2-14/16"	3-5/16"	3-10/16"	4"

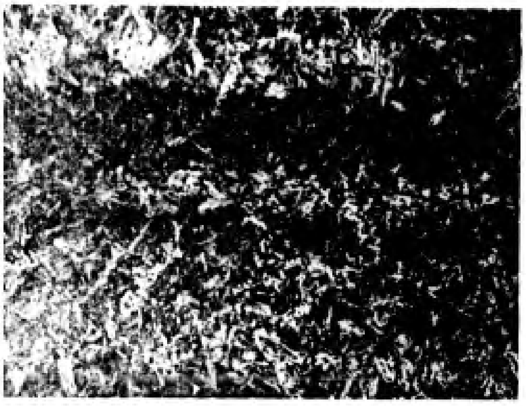
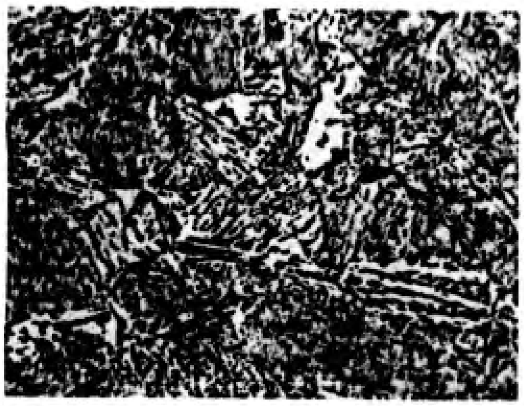
Microstructure and Remarks

The carbide needles indicate that low temperature bainite might be present in the martensitic structure. Only traces of a ferritic nonmartensitic austenite decomposition constituent are present. The microstructure is consistent with the reported quenching practice, since hardenability is adequate for the plate to have been completely quenched out (free of even traces of austenite decomposition products other than martensite) in an oil spray.

The fibre fracture has the characteristic crystalline appearance that is due to high hardness alone (not to poor shock resisting transformation products). The low Charpy values are what would be expected from the hardness. A companion plate from the series passed the ballistic shock test, but in view of the poor impact properties of the material, this only illustrates the mildness of the ballistic test.

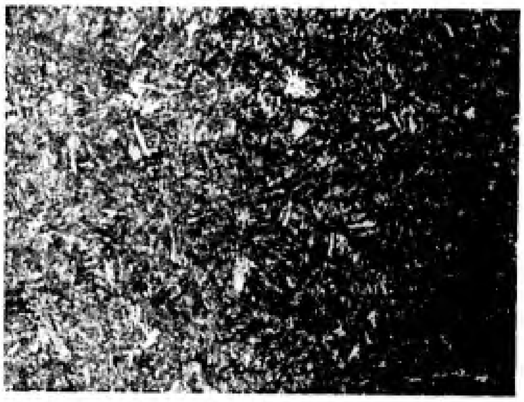
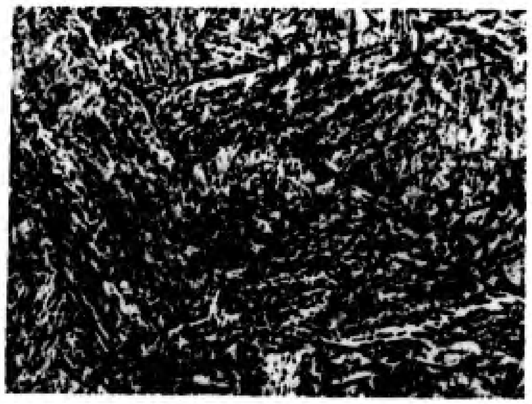
The excessive hardness is reflected in the PTP test by spalling of all the plates in the series.

Carnegie-Illinois 1½" Plate No. 129438-CTB
(Microspecimen etched with 4% Picral)

X200 **Center of Section** X1000

Moderate banding - A fairly large amount of tempered non-martensitic products is present in the light-etching bands (X1000 photo.).

X200 **Midway Between Surface and Center** X1000

No banding - Typical microstructure consists of tempered martensite plus a very small amount of tempered non-martensitic products.

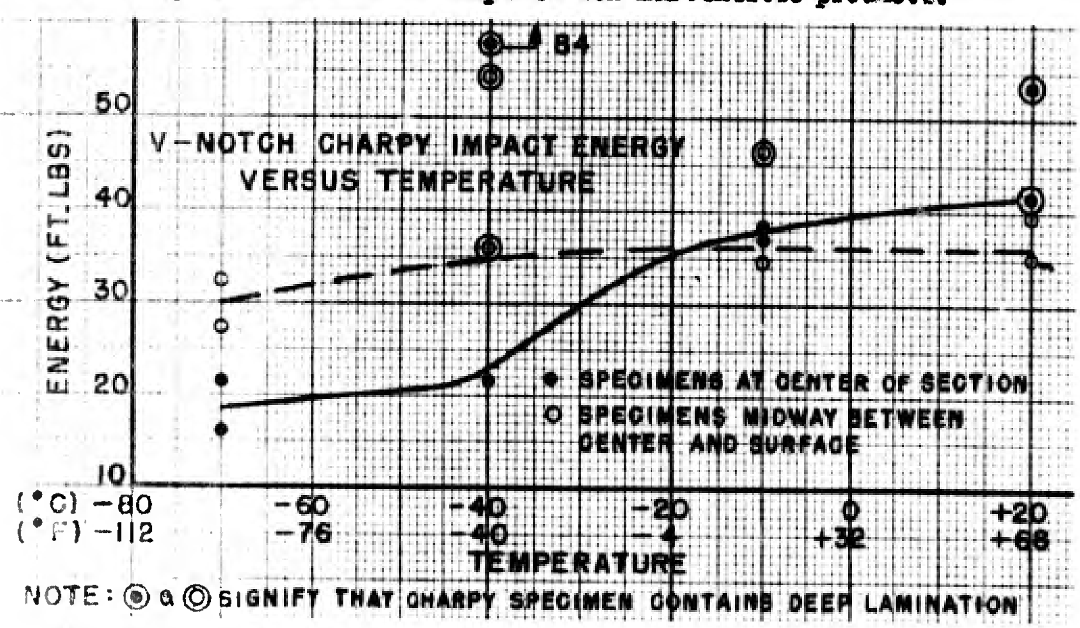


FIGURE 23

WTN.639-6814

DATA SHEET NO. 5

Carnegie-Illinois Steel Corp.

Heat No. 22345 | Plate No. 129438-CTB | Thickness 1.51"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.27	1.04	.21	.023	.018	1.00	.57	.38	-	-
Watertown Arsenal	.25	1.05	.27	.025	.014	.93	.62	.36	.06	.03

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1544	1½	3/4	Water
1040	2-1/4	1-1/4	Water

Physical Properties Reported

T.S.	143,000	% R.A.	65.0
Y.P.	129,000	Izod	-
% Elong.	20.5	Brinell	293

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-34°F.	75 mm T21 Slug	1261(+3)	Failed: CP-B.S. 5-1/4x7-3/4".	37 mm APC M51	No Test

In this heat: 1 plate of 5 failed shock.(Failed -34°F (CP-B.S.). Passed -24°F, -25.3°F, -34°F, and -35°F (no cracking).) 0 plates of 4 failed PTP.(Passed -24°F, -25.3°F, -34°F, and -35°F (borderline B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
311	302	285	C-	D	Mixed (Trace Cryst.)	Mixed (10% Cryst.)	Fibrous

Macrostructure and Microscopic Inclusion Determination

The steel was rolled in one direction predominantly. The long laminations seen in the steel soundness fractures are revealed by the macrostructure. Under the microscope these were found to have been caused by oxide inclusions in many long stringers throughout the section.

Jominy Hardenability

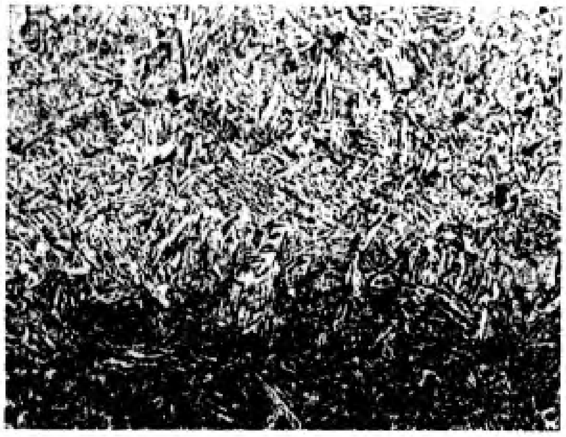
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
45.5	5	5-6	12/16"	1"	14/16"	1-1/16"

Microstructure and Remarks

In approximately one third of the banded structure at the center of the section, bands containing a fairly large quantity of nonmartensitic austenite decomposition products are present. The balance of the structure here is largely tempered martensite. Midway between plate center and surface the structure is predominantly tempered martensite also. Comparison between hardenability and microstructure indicates that the plate had been quenched very efficiently. The Charpy impact values are consistent with the microstructural variations; at the center of the section the energy drops off at -40°C, whereas the -40°C impact energy of the material midway between surface and center is equal to the room temperature energy and at -70°C has dropped very little. In addition, room temperature impact energy is equal to that of completely hardened armor of the same hardness. Only a small amount of crystallinity was revealed by the fracture tests.

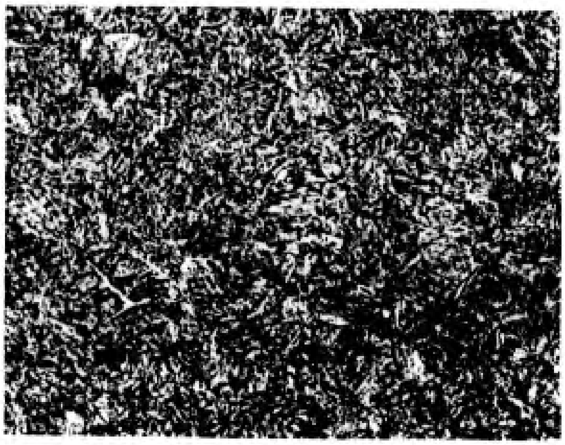
Since the plate failed the shock test by spalling, the failure is attributed to the poor steel quality and high hardness rather than to the poor microstructure at the center of the section. Poor steel quality, assisted by a Brinell of 311, is also considered responsible for the PTP spalling behavior of the series.

Disston 1½" Plate No. 2
(Microspecimen etched with 4% Picral)




X200 **Center of Section** X1000

Severely banded - The light-etching bands consist almost entirely of non-martensitic products and intercritical ferrite (X1000 photo.).




X200 **Midway Between Surface and Center** X1000

No banding - Typical structure is tempered martensite, intercritical ferrite, and a moderate amount of tempered non-martensitic products.

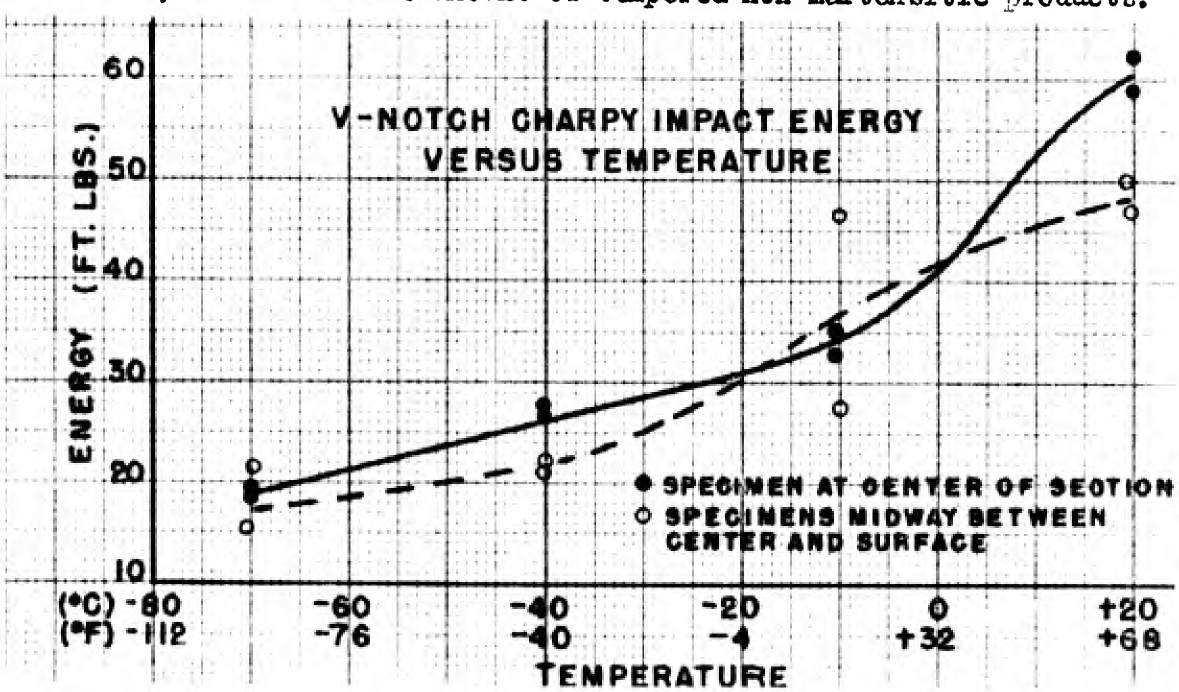


FIGURE 24

DATA SHEET NO. 6

Henry Disston and Sons, Inc.

Heat No. 22851 Plate No. 2 Thickness 1.51"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.21	.50	.25	.012	.014	3.10	.04	.29	.20	-
Watertown Arsenal	.19	.49	.27	.022	.013	3.05	.04	.30	.14	.01

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1425	$1\frac{1}{2}$	2	Water Spray
1100		2	Air

Physical Properties Reported

Brinell 255-269

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-25.5°F	75 mm T21 Slug	1261(+3)	Failed: Excessive cracking	37 mm APC M51	Passed: 2-1/4x$2\frac{1}{2}$".

In this heat: 2 plates of 4 failed shock. (Failed -25.5°F and -25.6°F (by excessive cracking). Passed -14°F and -25.3°F (no cracking).) 0 plates of 3 failed PTP. (Passed -11.5°F, -14°F, and -25.3°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
255	238	232	B	B	Mixed (30% Cryst.)	Mixed (Trace Cryst.)	Mixed (90% Cryst.)

Macrostructure and Microscopic Inclusion Determination

Macrostructures are similar in both rolling directions. Both macrostructure and microscopic inclusion determination indicated that the steel is clean and free from long stringers.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
44	3	2	<10/16"	10/16"	<7/16"	7/16"

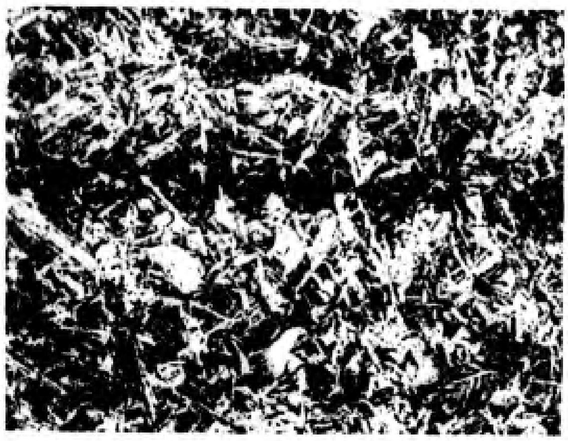
Microstructure and Remarks

In addition to intercritical ferrite caused by austenizing within the critical range, a great deal of austenite decomposition products other than martensite is present at the center of the section as a result of very low hardenability. Midway between center and surface the amount is much less but still appreciable. Charpy impact energy falls off rapidly at both locations with decrease of temperature and the fibre fracture is almost entirely crystalline. Accordingly, the plate cracked excessively under the impact of the ballistic shock test slug.

This series illustrates again that nickel cannot compensate for intercritical quenching and poor hardenability.

The excellent PTP behavior of the series is consistent with the excellent steel quality and proper hardness of the subject plate.

Standard (Great Lakes) 1½" Plate No. 1X4
(Microspecimen etched with 4% Picral)

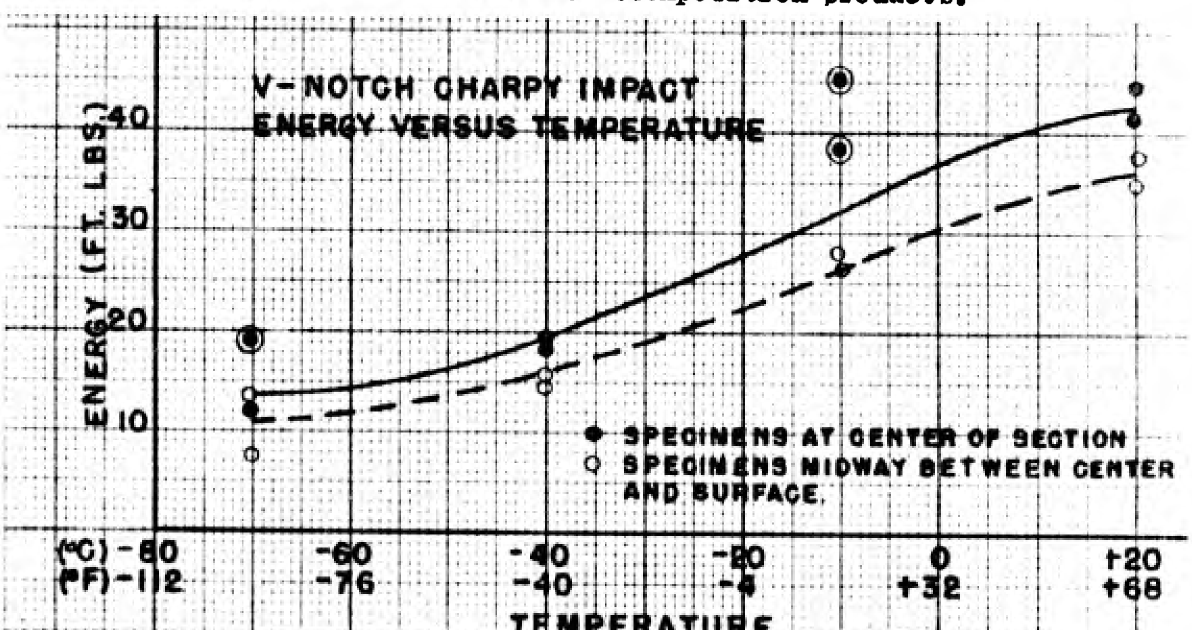



X200 Center of Section X1000

Moderate banding - Typical field shows tempered martensite and a great deal of tempered non-martensitic transformation products.


X200 Midway Between Surface and Center X1000

Slight banding - Typical field shows tempered martensite and some tempered non-martensitic austenite decomposition products.



NOTE: ◉ SIGNIFIES THAT CHARPY SPECIMEN CONTAINS A DEEP LAMINATION

FIGURE 25

WTN.639-68

DATA SHEET NO. 7

Standard Steel and Spring Co.
(Steel Supplied by Great Lakes Steel Corp.)

Heat No. GSG-724 | Plate No. 1X4 | Thickness 1.51"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Zr	Cu	Al
Company	.29	.89	.68	.030	.030	—	.61	.16	.08	-	-
Watertown Arsenal	.28	.90	.63	.022	.022	trace	.61	.15	.085	.10	.015

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1600		2-3/4	Water Spray
1170		2-3/4	Air

Physical Properties Reported

T.S.	115,200L,	115,500T
Y.P.	95,750L,	97,500T
% Elong.	20.0L	18.0T
% R.A.	62.3L	54.7T
Izod	—	—
Brinell	255-286	

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-22°F.	75 mm T21 Slug	1250(-5)	Failed: Broke 3 pieces	37 mm APC M51	No test.

In this heat: 3 plates of 3 failed slug shock test.(Failed -18°F, -22°F, and -22°F (all broke into pieces and one B.S).) 2 plates of 2 passed 75 AP at 25° obliquity.(Passed -17°F and -17°F. (No cracking.)) 0 plates of 2 failed PTP. (Passed -17°F and -17°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
269	262	245	E	E	Mixed (25% Cryst.)	Mixed (10% Cryst.)	Mixed (65% Cryst.)

Macrostructure and Microscopic Inclusion Determination

The steel was straightaway rolled. The laminations responsible for the "E" steel soundness rating are revealed by the macrostructure but to a lesser extent. Under the microscope these were found to be caused by oxide inclusions in many long stringers throughout the section.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
48	4	6	10/16"	13/16"	15/16"	1-3/16"

Microstructure and Remarks

As a result of very poor hardenability, a great deal of nonmartensitic transformation products is present at the center of the section. Midway between the center and surface, undesirable constituents are present but too a much lesser extent. (It must be noted, however, that the photomicrographs here illustrate only the average condition.) Charpy impact at both locations decreases rapidly with decrease of testing temperature and the fibre fracture is largely crystalline even though deep laminations are present. The plate behaved in a very brittle manner when subjected to ballistic shock, as would be expected from the poor impact properties of the material.

It should be noted that two companion plates of the series passed the PTP test at -17°F although the steel quality of the series, judged by that of the subject plate and Plate No. 1X5, was very poor.

Standard Steel and Spring Co.
(Steel Supplied by Great Lakes Steel Corp.)

Heat No. GSG-724 Plate No. 1X4 Thickness 1.51"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Zr	Cu	Al
Company	.29	.89	.68	.030	.030	—	.61	.16	.08	-	-
Watertown Arsenal	.28	.90	.63	.022	.022	trace	.61	.15	.085	.10	.015

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1600		2-3/4	Water Spray
1170		2-3/4	Air

Physical Properties Reported

T.S.	115,200L,	115,500T
Y.P.	95,750L,	97,500T
% Elong.	20.0L	18.0T
% R.A.	62.3L	54.7T
Izod	—	—
Brinell	255-286	

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-22°F.	75 mm T21 Slug	1250(-5)	Failed: Broke 3 pieces	37 mm APC M51	No test.

In this heat: 3 plates of 3 failed slug shock test. (Failed -18°F, -22°F, and -22°F (all broke into pieces and one B.S).) 2 plates of 2 passed 75 AP at 25° obliquity. (Passed -17°F and -17°F. (No cracking.)) 0 plates of 2 failed PTP. (Passed -17°F and -17°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
269	262	245	E	E	Mixed (25% Cryst.)	Mixed (10% Cryst.)	Mixed (65% Cryst.)

Macrostructure and Microscopic Inclusion Determination

The steel was straightaway rolled. The laminations responsible for the "E" steel soundness rating are revealed by the macrostructure but to a lesser extent. Under the microscope these were found to be caused by oxide inclusions in many long stringers throughout the section.

Jominy Hardenability

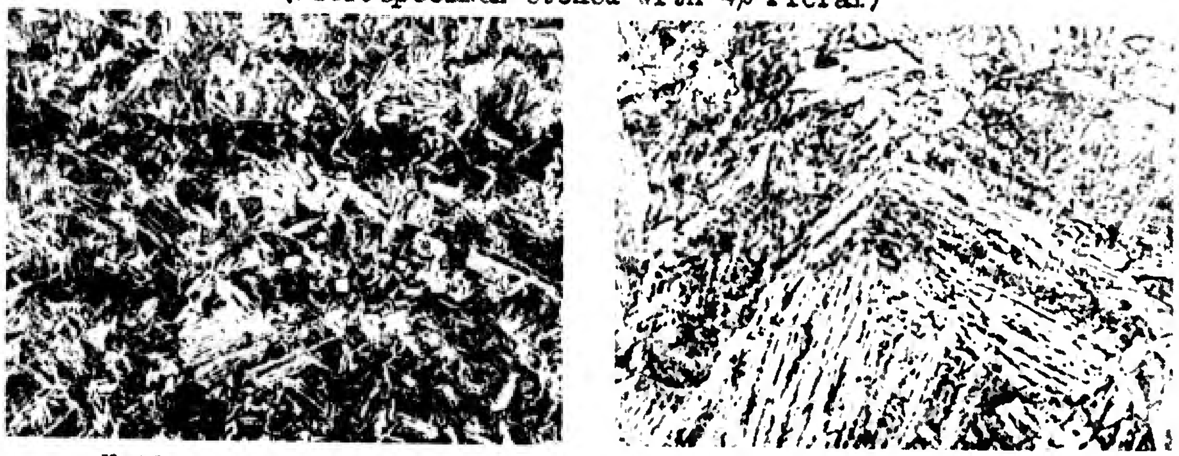
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
48	4	6	10/16"	13/16"	15/16"	1-3/16"

Microstructure and Remarks

As a result of very poor hardenability, a great deal of nonmartensitic transformation products is present at the center of the section. Midway between the center and surface, undesirable constituents are present but too a much lesser extent. (It must be noted, however, that the photomicrographs here illustrate only the average condition.) Charpy impact at both locations decreases rapidly with decrease of testing temperature and the fibre fracture is largely crystalline even though deep laminations are present. The plate behaved in a very brittle manner when subjected to ballistic shock, as would be expected from the poor impact properties of the material.

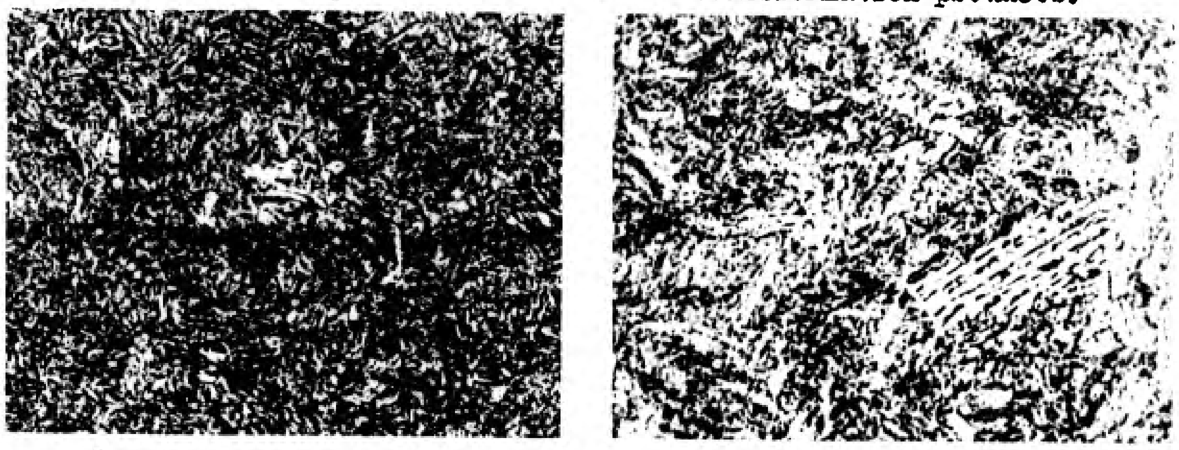
It should be noted that two companion plates of the series passed the PTP test at -17°F although the steel quality of the series, judged by that of the subject plate and Plate No. 1X5, was very poor.

Standard (Great Lakes) 1½" Plate No. 1X5
(Microspecimen etched with 4% Picral)



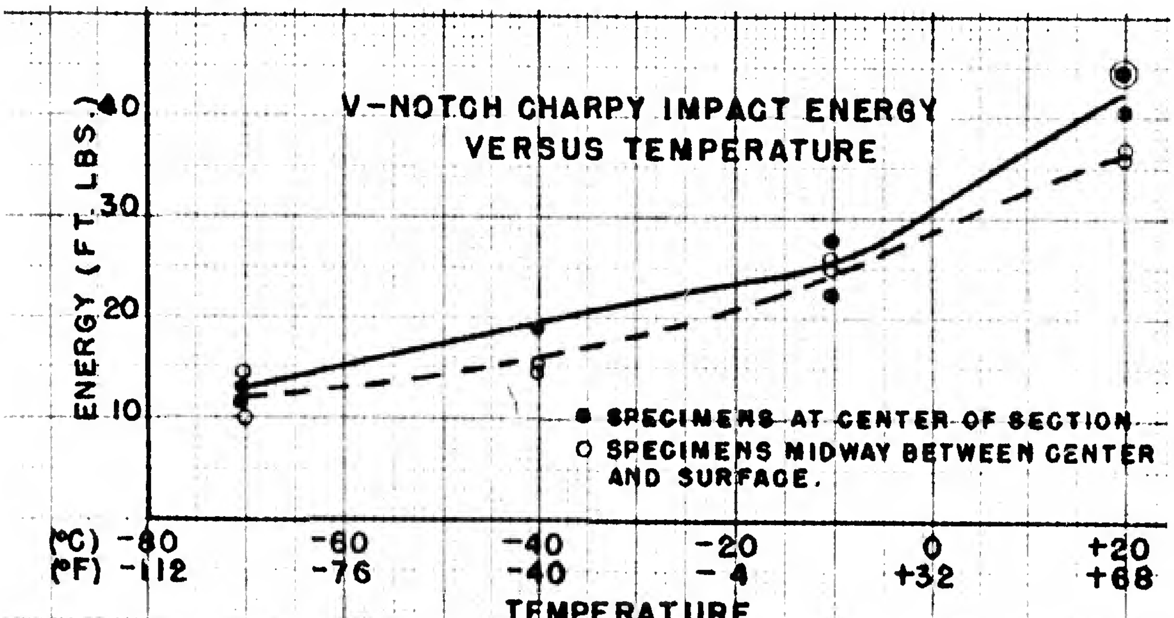
X200 Center of Section X1000

Moderate banding - Typical microstructure is tempered martensite and a great deal of tempered non-martensitic transformation products.



X200 Midway Between Surface and Center X1000

Slight banding - Typical microstructure is tempered martensite and some tempered non-martensitic transformation products.



NOTE: ◉ SIGNIFIES THAT CHARPY SPECIMEN FRACTURE CONTAINS A DEEP LAMINATION.

FIGURE 26

DATA SHEET NO. 8

Standard Steel and Spring Co.
(Steel Supplied by Great Lakes Steel Corp.)

Heat No. GSG-724 Plate No. 1X5 Thickness 1.50"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Zr	Cu	Al
Company	.29	.89	.68	.030	.030	-	.61	.16	.08	-	-
Watertown Arsenal	.28	.90	.63	.022	.022	trace	.62	.15	.11	.10	.015

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1600		2-3/4	Water Spray
1170		2-3/4	Air

Physical Properties Reported

Brinell 248-286

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-18°F.	75 mm T21 Slug	1248(-5)	Failed: Broke 2 pieces and 7x9-3/4" B.S.	37 mm APC M51	No Test

In this heat: 3 of 3 failed slug shock test. (Failed -18°F, -22°F, and -22°F (all broke into pieces and one B.S).) 2 plates of 2 passed 75 AP at 25° obliquity. (Passed -17°F and -17°F (no cracking).) 0 plates of 2 failed PTP. (Passed -17°F and -17°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
269	259	248	E	E	Mixed (25% Cryst.)	Mixed (5% Cryst.)	Mixed (65% Cryst.)

Macrostructure and Microscopic Inclusion Determination

The steel was straightaway rolled. The laminations responsible for the "E" steel soundness rating are revealed by the macrostructure but to a lesser extent. Under the microscope these were found to have been caused by oxide inclusions in many long stringers throughout the section. (The inclusion condition in this plate is identical to that of its companion plate No. 1X4).

Jominy Hardenability

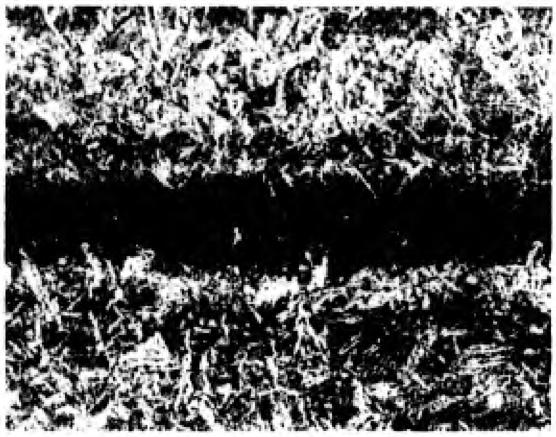
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
48.5	5	6-7	12/16"	1"	1"	1-4/16"

Microstructure and Remarks

This plate is similar to its companion plate No. 1X4 in microstructure, V-notch Charpy impact, and fibre fracture and, therefore, behaved similarly under ballistic shock. (See Data Sheet No. 7.) The back spall punched out by the slug was caused by the poor steel quality. A third plate in the series that was tested with the slug also broke into pieces.

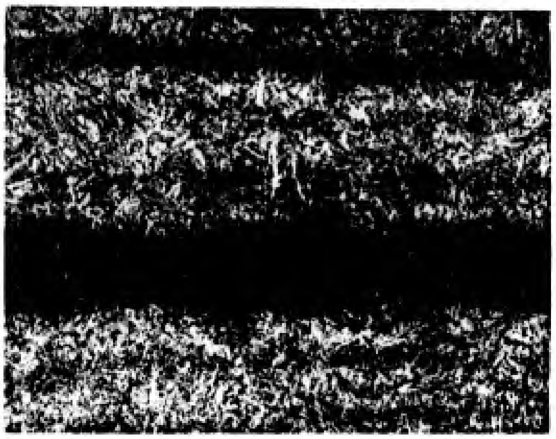
The inadequacy of the test formerly used to estimate the shock resistance of armor, a 75 mm AP projectile fired at 25° obliquity, is illustrated by this series, wherein two plates, shock tested in this manner, gave passing performance.

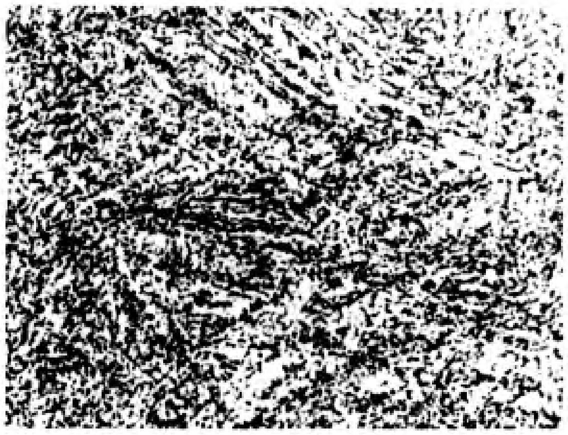
Republic 1½" Plate - Heat No. RH-50307G
(Microspecimen etched with 4% Picral)



X200 **Center of Section** X1000

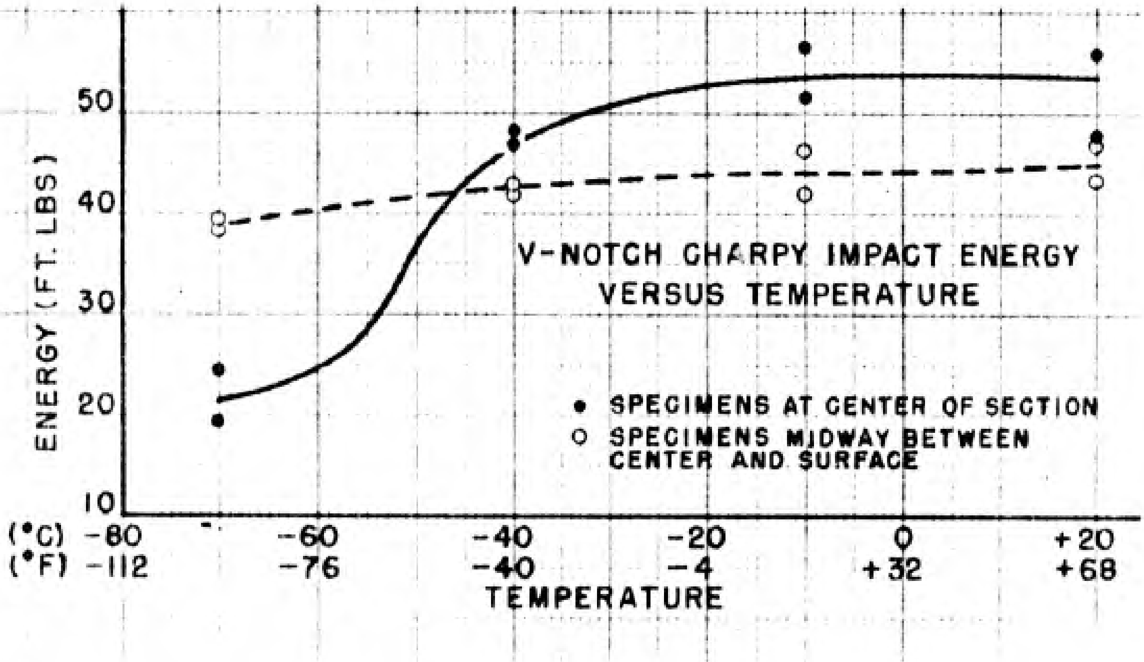
Severe banding - Light-etching matrix consists of tempered martensite and a great deal of tempered non-martensitic products (X1000 photo.).





X200 **Midway Between Surface and Center** X1000

Severe banding - Light-etching matrix consists of tempered martensite and a small amount of tempered non-martensitic products (X1000 photo.).



DATA SHEET NO. 9

Republic Steel Corp.

Heat No. RH-50307G   Plate No. ----   Thickness 1.48"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.27	.80	.27	.019	.018	.95	.71	.49	-	-
Watertown Arsenal	.27	.88	.27	.020	.014	.80	.73	.41	.12	.02

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1600			Water
1200			Air

Physical Properties Reported

T.S.	119,500	% R.A.	17.07
Y.P.	103,000	Izod	47
% Elong.	23.9	Brinell	255-262

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-34°F.	75 mm T21 Slug	1229(-5)	Passed: No cracking.	37 mm APC M51	Failed: 3-1/4x3-1/4" with B.S.

In this heat: 0 plates of 4 failed shock. (Passed -23°F, -24°F, -33°F, -34°F (no cracking.).) 1 plate of 4 failed PTP. (Failed -34°F (excessive B.S.). Passed -23°F and -24°F (No B.S.). Passed -33°F (allowable B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
245	226	220	C-	D	Fibrous	Fibrous	Fibrous

Macrostructure and Microscopic Inclusion Determination

The steel was rolled in one direction predominantly. The extreme "woodiness" of the steel soundness fracture is shown by the macrostructure to have been caused by numerous short stringers throughout the section, but the cause of the "D" fracture rating is not apparent. Microscopic examination showed in addition to numerous thin elongated inclusions (which are responsible for the "woodiness") a moderate number of long stringers of oxides. The latter appear to have caused the "D" fracture.

Jominy Hardenability

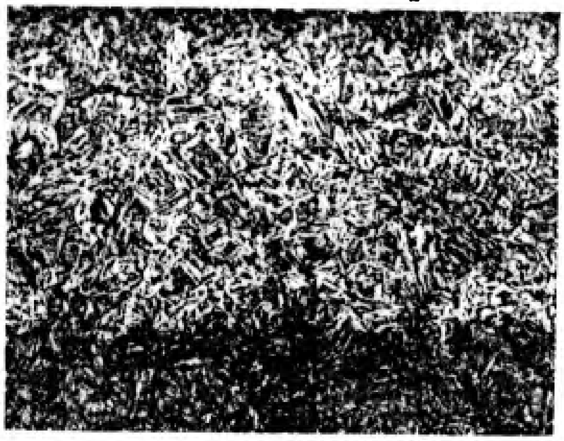
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
46.5	5	6	12/16"	1"	15/16"	1-3/16"

Microstructure and Remarks

The steel having inadequate hardenability, a great deal of nonmartensitic transformation products occurred at the center of the section. The low hardness (220 Brinell) at this region (perhaps assisted by the excessive nonmetallic content and unidirectional properties, and resulting very "woody" fracture) was sufficient to counteract the poor microstructure, however, and the material retains its room temperature impact properties down to almost -40°C. The Charpy impact values midway between the surface and center are consistent with the apparently predominantly tempered martensite structure at this location in that the room temperature Charpy impact energy is retained almost down to -70°C. The Charpy level, on the other hand, is much lower than expected for completely quench hardened armor of the same Brinell (245-226) and mechanical treatment, but this may be due largely to the unusual "woodiness" of the fractures. With room temperature Charpy values being retained down to about -40°C throughout the section, the fibre fracture was completely fibrous and ballistic shock performance of the series was excellent.

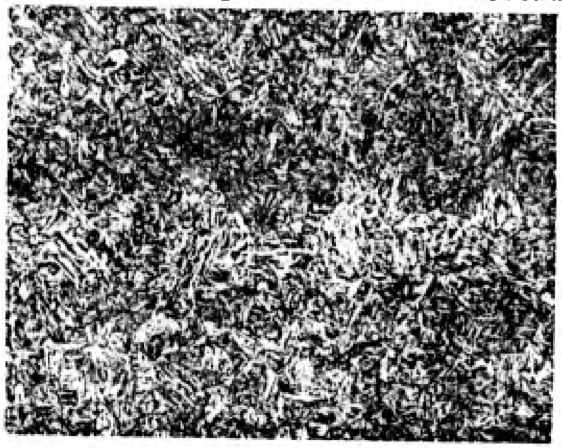
The failure of this plate to pass the PTP test at -34°F is attributed to the oxide stringers in the material. It should be noted that spalling did not occur in the series until the testing temperature had been lowered to -33°F.

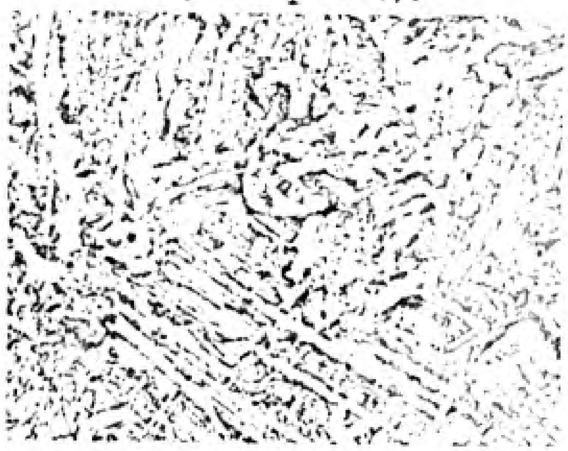
Disston 1½" Plate No. 5
(Microspecimen etched with 4% Picral)



X200 **Center of Section** X1000

Severely banded - Light-etching bands consist almost entirely of non-martensitic products and intercritical ferrite (X1000 photo.).





X200 **Midway Between Surface and Center** X1000

Some banding - Microstructure of the light-etching bands is intercritical ferrite, tempered martensite, and non-martensitic products.

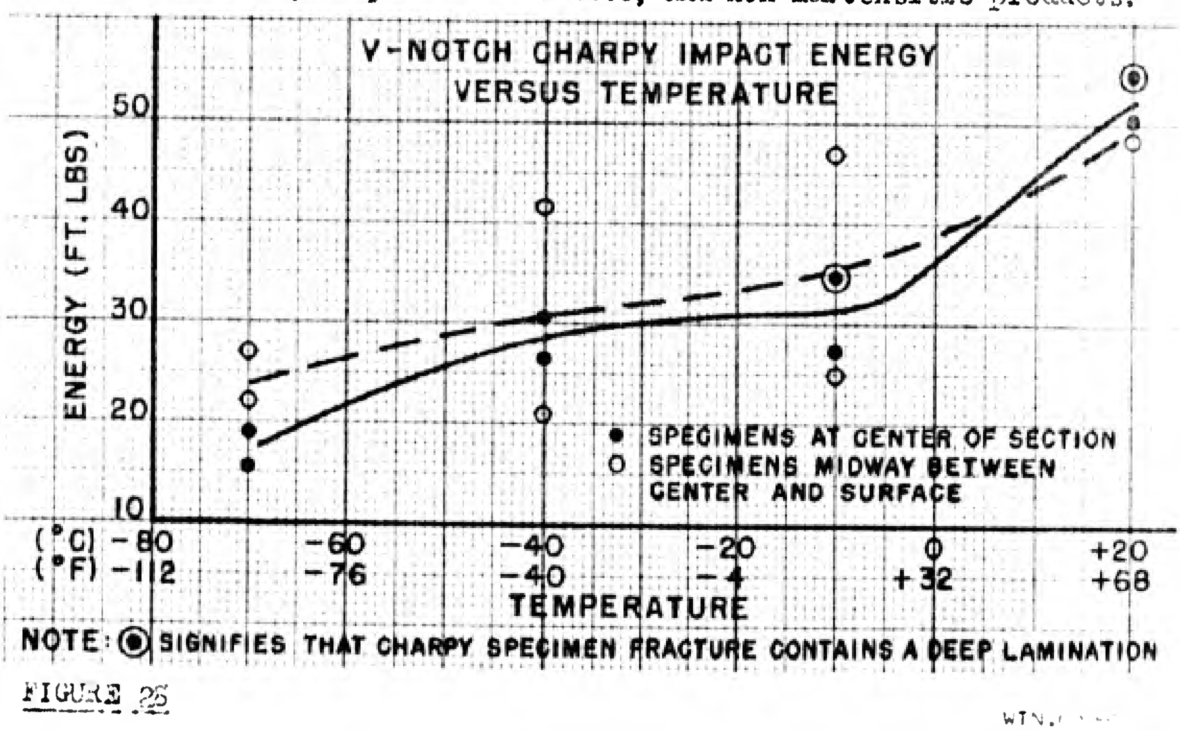


FIGURE 25

DATA SHEET NO. 10

Henry Disston and Sons, Inc.

Heat No. 22851 Plate No. 5 Thickness 1.50"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.21	.50	.25	.012	.014	3.10	.04	.29	.20	-
Watertown Arsenal	.20	.51	.28	.021	.013	3.09	.04	.29	.14	.01

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1425	1½	2	Water Spray
1100		2	Air

Physical Properties Reported

Brinell 248-262

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-25.3°F.	75 mm T21 Slug	1255(+5)	Passed: No cracking.	37 mm APC M51	Passed: 2-9/16x2-3/4".

In this heat: 2 plates of 4 failed shock.(Failed -25.5°F and -25.6°F (by excessive cracking). Passed -14°F and -25.3°F (no cracking).) 0 plates of 3 failed PTP.(Passed -11.5°F, -14°F, and -25.3°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
251	255	255	B-	B	Mixed (5% Cryst.)	Fibrous	Mixed (60% Cryst.)

Macrostructure and Microscopic Inclusion Determination

Macrostructures are approximately similar in both rolling directions. Both macrostructure and microscopic inclusion determination indicated that the steel is fairly clean and free from long stringers. (The inclusion condition in this plate is similar to that of its companion plate No. 2.)

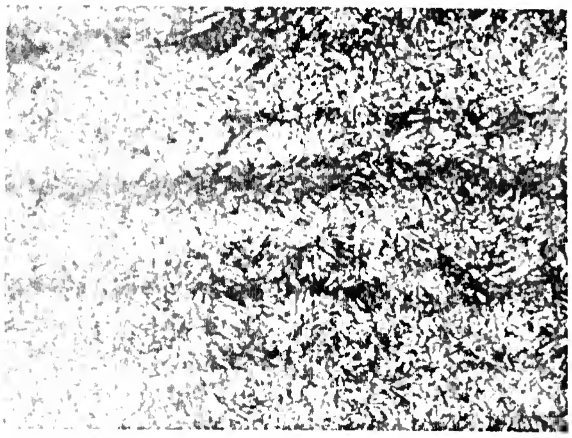
Jominy Hardenability

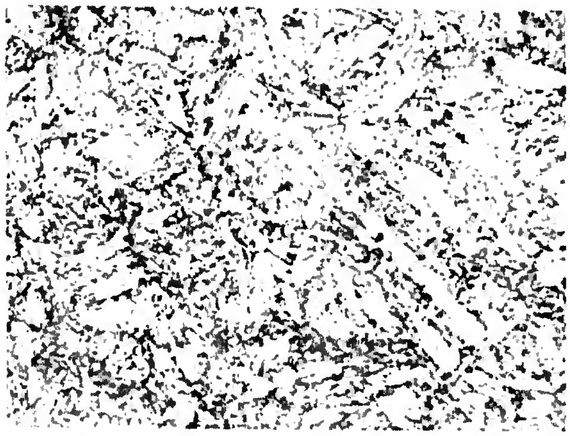
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
44.5	4	2	10/16"	13/16"	<7/16"	7/16"

Microstructure and Remarks

Microstructure, V-notch Charpy impact properties, and fibre fracture of this plate and its companion plate No. 2 are similar. (See Data Sheet No. 6.) From this investigation no reason is evident for the different behaviors of the two plates when shock tested ballistically. In view of the poor shock properties possessed by the subject plate, it would be expected that it also would have failed to resist the slug, and it should be noted that in this series two out of four plates did give unsatisfactory ballistic shock performance.

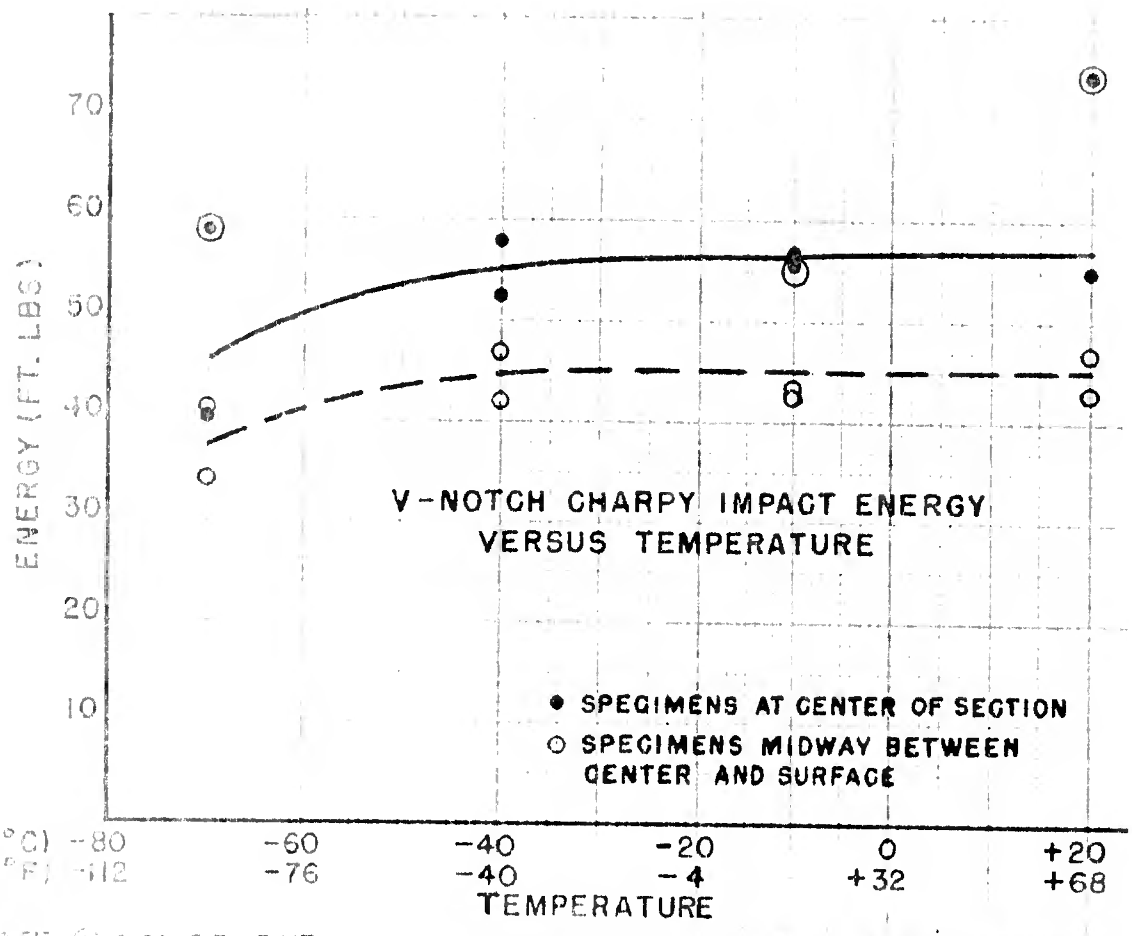
Standard (Jones and Laughlin) 1½" Plate No. M1X3
(Microspecimen etched with 4% Picral)





X200 Center of Section X1000

Moderate banding - The structure throughout the section consists of acicular tempered martensite.



NOTE: ⊙ SIGNIFIES THAT CHARPY SPECIMEN FRACTURE CONTAINS A DEEP LAMINATION

DATA SHEET NO. 11

Standard Steel and Spring Co.
(Steel Supplied by Jones and Laughlin Steel Corp.)

Heat No. GSJ-335 Plate No. M1X3 Thickness 1.51"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	B	Cu	Al
Company	.27	1.59	.25	.016	.021	—	—	.41	—	—	—
Watertown Arsenal	.27	1.59	.25	.019	.017	trace	.02	.41	.0009	.01	.04

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant

Physical Properties Reported

T.S.	137,200L, 135,600T
Y.P.	129,200L, 126,800T
% Elong.	15.5L, 17.0T
% R.A.	57.2L, 59.7T
Izod	-- --
Brinell	255-286

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-30°F.	75 mm T21 Slug	1247(-8)	Passed: No cracking.	37 mm APC M51	Passed: 2-1/4x2-5/16".

In this heat: 0 plates of 4 failed shock. (Passed -18.5°F, -18.5°F, -29°F, and -30°F (no cracking).) 0 plates of 4 failed PTP. (Passed -18.5°F, -18.5°F, -29°F, and -30°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
285	285	285	B-	B-	Fibrous	Fibrous	Fibrous

Macrostructure and Microscopic Inclusion Determination

Macrostructures are similar in both rolling directions. Both macrostructure and microscopic inclusion determination indicated that the steel is moderately dirty but free of long stringers.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
50.5	24	>40	3-4/16"	3-11/16"	>3-13/16"	>3-13/16"

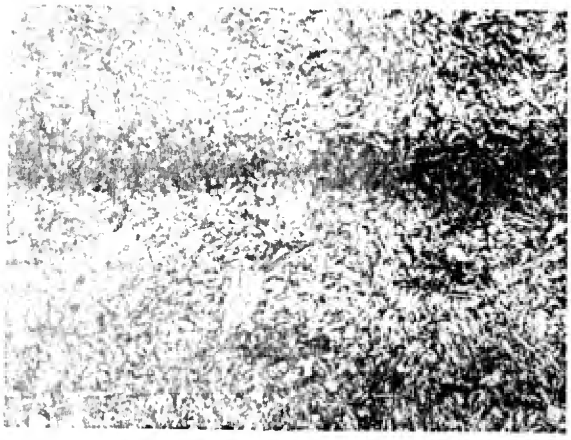
Microstructure and Remarks

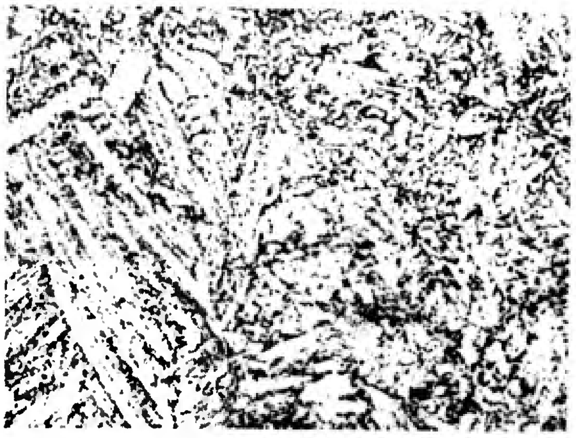
Possessed of excellent hardenability, this material is revealed by microscopic examination to have been completely quench hardened. The resultant excellent Charpy impact values and fibrous fracture are reflected in the ballistic shock test by the satisfactory performance of every plate of the series.

Since Brinell is uniform throughout the section, the explanation for the Charpy curve of the material at the center of the section being higher than the curve of the material midway between center and surface is probably some reason other than differences in nonmetallic content at the two locations, the center region being the dirtier. The Charpy fractures did indicate that this was indeed the case. The room temperature energy being equal to that of completely quenched out material of the same hardness and being retained down to even below -40°C, the Charpy curves verify the microscopic examination, indicating that the microstructure is entirely tempered martensite.

No spalling tendencies were revealed in any of the plates of the series by the PTP penetrations, as is to be expected from the excellent steel soundness and proper Brinell hardness of the plate examined.

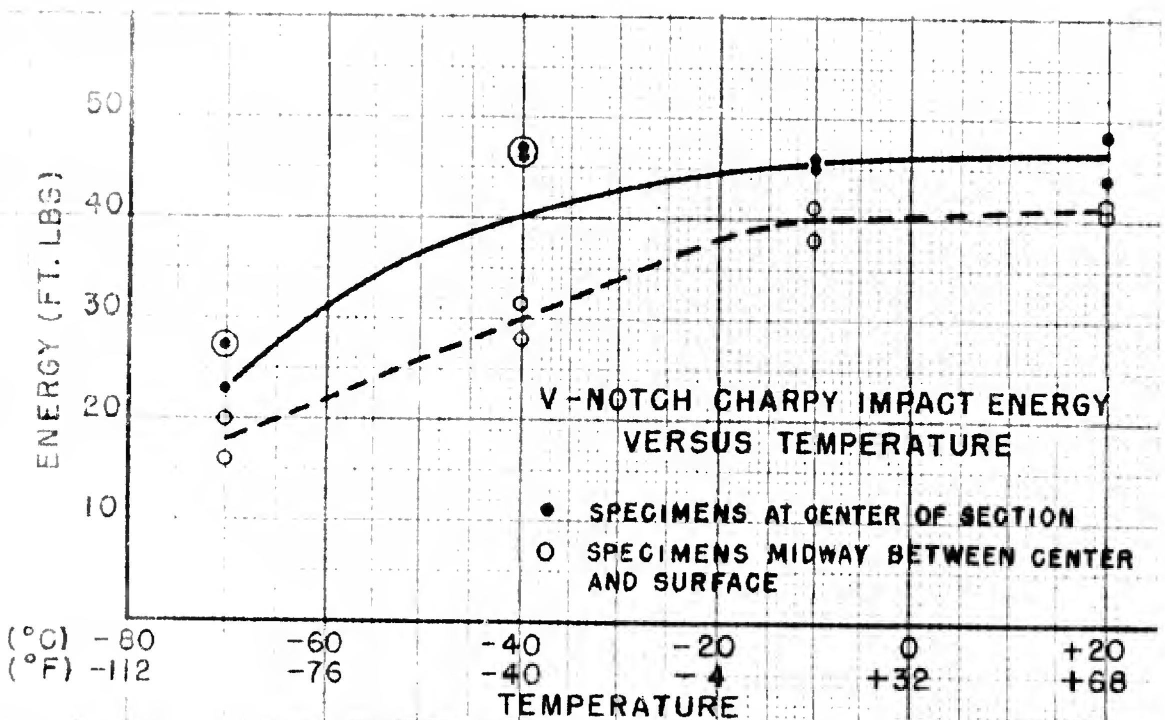
Standard (Youngstown) 1½" Plate No. 1X5
(Microspecimen etched with 4% Picral)





X200 Center of Section X1000

Moderate banding - Typical microstructure appears to be only acicular tempered martensite and traces of a ferritic non-martensitic transformation product.



NOTE: ⊙ SIGNIFIES THAT CHARPY SPECIMEN FRACTURE CONTAINS A DEEP LAMINATION

FIGURE 30

WTN,639-6821

DATA SHEET NO. 12

Standard Steel and Spring Co.
(Steel Supplied by The Youngstown Sheet and Tube Co.)

Heat No. GSY-75-10 Plate No. 1X5 Thickness 1.51"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.27	1.86	.19	.022	.037	.05	-	.38	-	-
Watertown Arsenal	.29	1.85	.21	.020	.037	.09	.02	.37	.06	.03

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1600		2-3/4	Water Spray
1170		2-3/4	Air

Physical Properties Reported

T.S.	123,000L, 123,500T
Y.P.	106,500L, 106,800T
% Elong.	22.5L, 19.5T
% R.A.	70.1L, 56.1T
Izod	- -
Brinell	255-269

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-16.5°F	75 mm T21 Slug	1265(+7)	Passed: No cracking.	37 mm APC M51	Passed: 2-1/4"x2-3/8".

In this heat: 0 plates of 4 failed shock. (Passed -16.5°F, -18.5°F, -31°F, and -33°F (no cracking).) 0 plates of 4 failed PTP. (Passed -16.5°F, -18.5°F, -31°F, and -33°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
259	265	262	D Centerline	C	Fibrous	Fibrous	Fibrous

Macrostructure and Microscopic Inclusion Determination

The plate was straightaway rolled. Macrostructure checks the steel soundness fracture. Macroscopic examination revealed that the "D" rating was due to oxide inclusions in long stringers mainly at the center of the section.

Jominy Hardenability

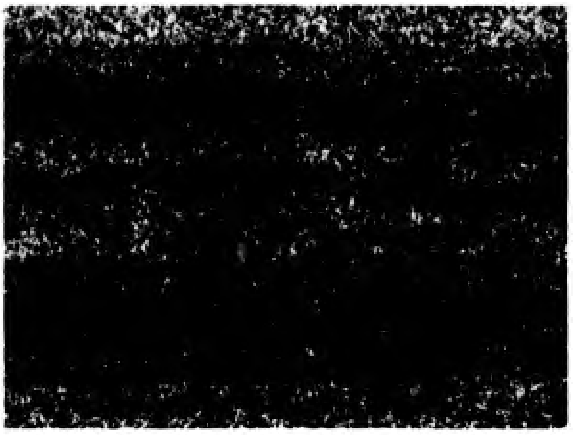
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
49	22	40	3-1/16"	3-8/16"	>3-13/16"	>3-13/16"

Microstructure and Remarks

From the appearance of the tempered microstructure the plate appears to have been completely quench hardened except for traces of a ferritic non-martensitic austenite decomposition product. It is seen, however, that room temperature Charpy impact energy at both testing locations decreases at -40°C. Since it does not seem likely that this is due to the minute quantity of the ferritic constituent, apparently some other constituent which cannot be detected in the tempered structure is present in the steel. The plate was not quenched very efficiently, for examination of the Jominy bar revealed that the plate under a water spray (H=1.8) could have been quenched to martensite free of all other transformation products except traces of the ferrite-carbide product.

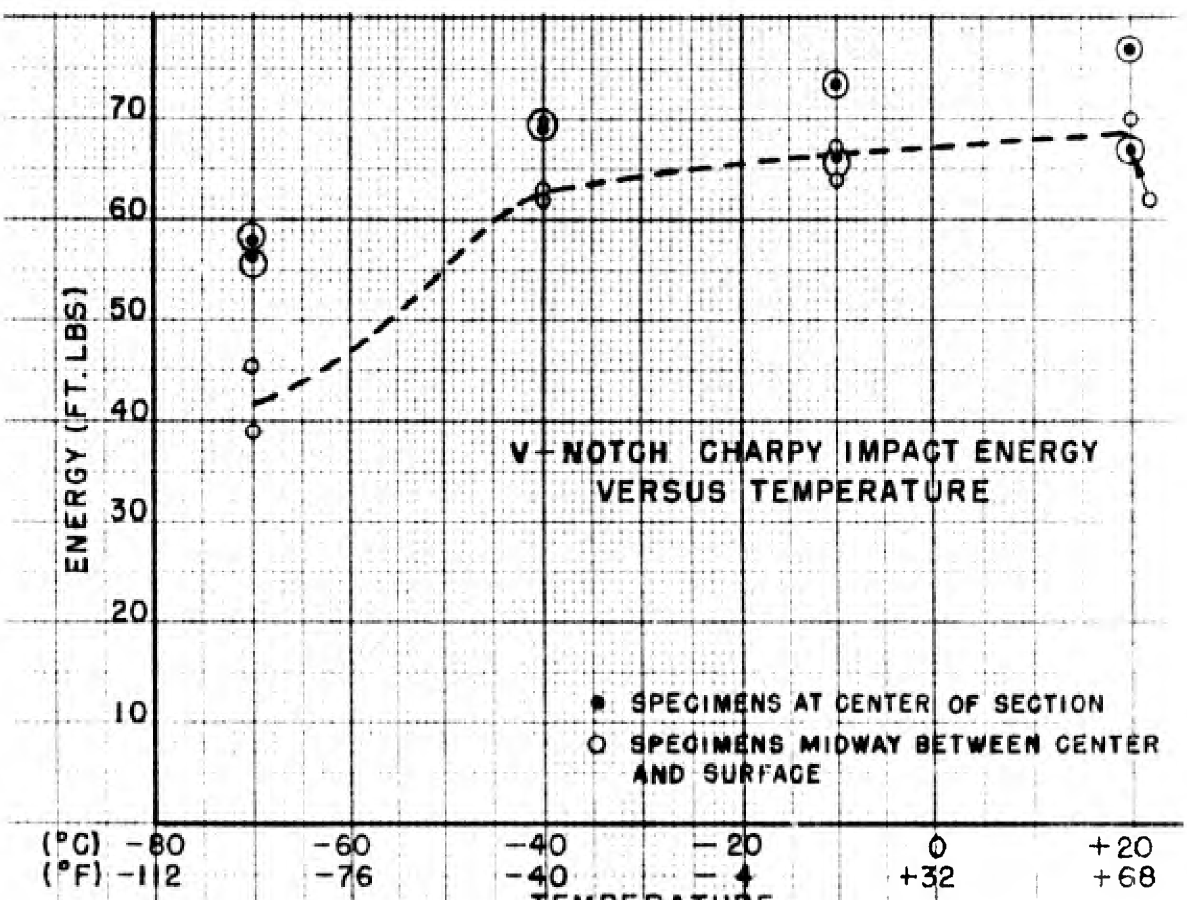
The fiber fracture is wholly fibrous, but a deep lamination is present which may have influenced the attainment of complete fibre. Resistance of the entire series to ballistic shock was excellent, as would be expected, because impact properties although not optimum are nevertheless good. No spalling occurred even at the lowest PTP testing temperature of the series although steel quality, judged by the plate examined, was [illegible]ewhat poor.

Van Dorn Iron Works 1½" Plate No. 4
(Microspecimen etched with 4% Picral)



X200 Center of Section X1000

Prominent banding - The matrix structure consists of tempered martensite plus a very small amount of tempered non-martensitic austenite decomposition products.



NOTE: ⊙ SIGNIFIES THAT CHARPY SPECIMEN FRACTURE CONTAINS DEEP LAMINATIONS

FIGURE 31

DATA SHEET NO. 13

Van Dorn Iron Works Co.

Heat No. H-20542 Plate No. 4 Thickness 1.55"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.26	.92	.26	.024	.016	1.21	1.05	.66	-	-
Watertown Arsenal	.30	.93	.26	.019	.021	1.22	1.03	.61	.12	.02

Heat Treatment				Physical Properties Reported
Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant	
				Brinell 242-282

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-30°F.	75 mm T21 Slug	1260(-15)	Passed: No cracking.	37 mm APC M51	Passed: 2"x2-5/16".

In this heat: 0 plates of 5 failed shock. (Passed -14.5°(1391(+109) f/s), -16.5°F, -25°F, -28°F, and -30°F (no cracking).) 0 plates of 5 failed PTP. (Passed -14.5°F, -16.5°F, -25°F, -28°F, and -30°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Trans.
248	248	248	D Centerline	D	Fibrous	Fibrous	Fibrous

Macrostructure and Microscopic Inclusion Determination

Macrostructures are similar in both rolling directions. Concentrations of stringers are present in the macrostructure at the center of the section, bu the steel appears cleaner than would be expected from the "D" steel soundness fracture. The microscope revealed thin elongated inclusions in concentrations mainly at the center of the section.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
51.5	24	>40	3-4/16"	3-11/16"	> 3-13/16"	> 3-13/16".

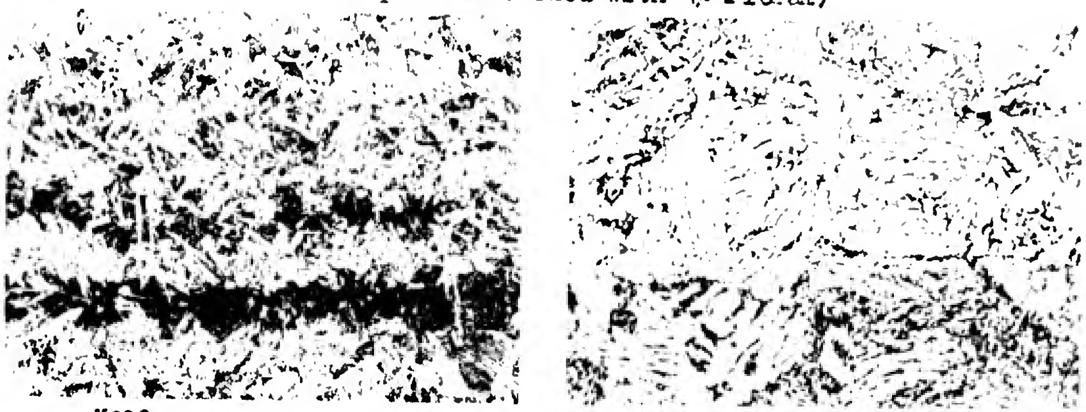
Microstructure and Remarks

The plate having excellent hardenability, only a very small amount of non-martensitic products occurred at the center of the section. Resulting ballistic shock performance of the entire series was, therefore, excellent.

The hardenability of the steel is sufficient for the plate to have been quench hardened throughout to martensite free of even traces of other transformation products, had a quenching medium of efficiency H=1.8 been used. Midway between surface and center the room temperature Charpy energy is retained down to almost -40°C. Impact properties at the center of the section cannot be determined from the Charpy tests because deep laminations are present in the fractures. Likewise, since pronounced shelving is present at the center of the section, the impact toughness of the material cannot be judged from the wholly fibrous appearance of the fibre test fracture.

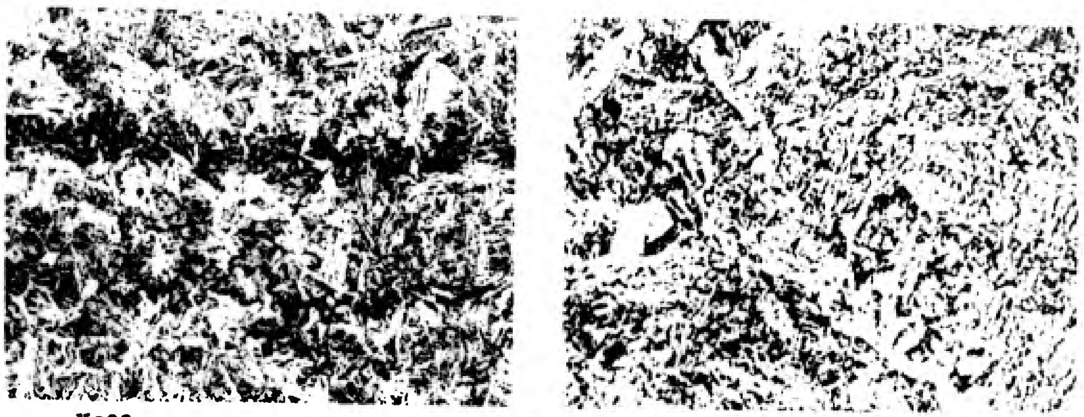
The PTP test was not influenced by the centerline shelving even at the lowest testing temperature of the series. The ballistic and steel soundness test data for this series, the Youngstown series, and the Great Lakes series are evidence that the PTP test applied to 1½" rolled armor at Camp Shilo was inadequate.

Standard (Great Lakes) 2" Plate No. 1X1
(Microspecimen etched with 4% Picral)



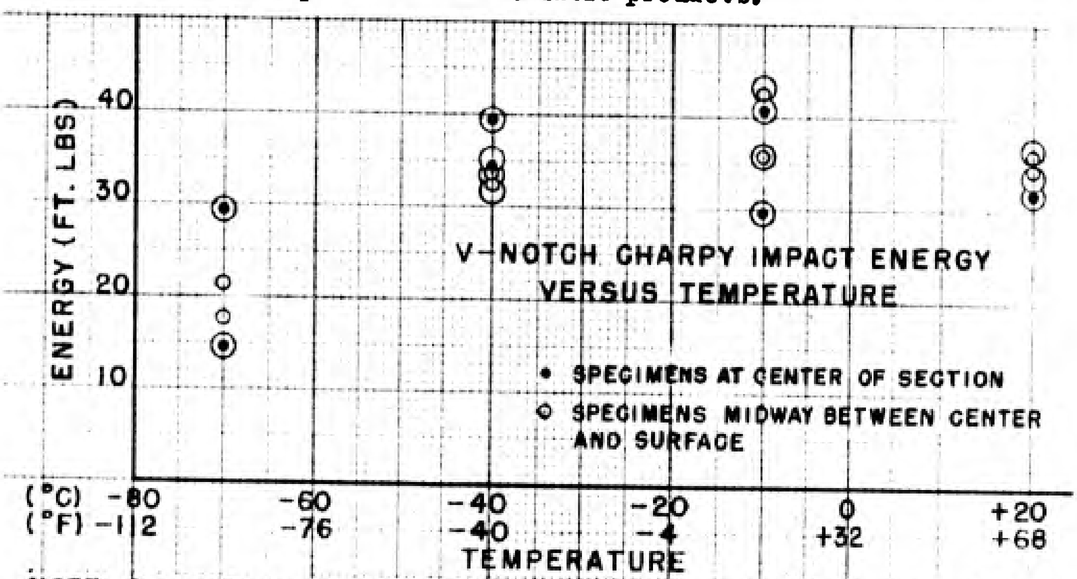
X200 **Center of Section** X1000

Moderate banding - Typical microstructure is largely tempered non-martensitic austenite decomposition products.



X200 **Midway Between Surface and Center** X1000

Some banding - Typical microstructure is tempered martensite and a large amount of tempered non-martensitic products.



NOTE: ⊙ AND ◎ SIGNIFY EITHER E STEEL QUALITY OR DEEP LAMINATION IN FRACTURE

FIGURE 32

DATA SHEET NO. 14

Standard Steel and Spring Co.
(Steel Supplied by Great Lakes Steel Corp.)

Heat No. GSG-635 | Plate No. 1X1 | Thickness 2.05"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Zr	Cu	Al
Company	.30	.83	.80	.026	.016	-	.61	.16	.08	-	-
Watertown Arsenal	.29	.85	.75	.022	.014	trace	.60	.16	.085	.08	.015

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1600		3-1/4	Water Spray
1160		3-1/4	Air

Physical Properties Reported

T.S.	126,100L,	127,500T
Y.P.	109,500L,	111,500T
% Elong.	17.5L,	12.0T
% R.A.	57.3L,	37.3T
Izod	--	--
Brinell	255-269	

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-15°F.	75 mm T21 Slug	Est.1525(+0)	Failed: 9½" cracking, side of bulge.	37 mm APC M51	Failed: 4-1/4x 5" B.S.

In this heat: 2 plates of 4 failed shock.(Failed -15°F and -15°F (by excessive cracking). Passed -12°F and -15°F (no cracking).)4 of 4 plates failed PTP. (Failed -12°F, -15°F, -15°F, and -15°F (by excessive B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
281	269	238	E	E	Mixed (Trace Cryst.)	Fibrous	Mixed (5% Cryst.)

Macrostructure and Microscopic Inclusion Determination

The plate was straightaway rolled. Macrostructure checks the steel soundness fracture. Microscopic examination revealed that the"E" rating was due to oxide inclusions in many long stringers throughout the section.

Jominy Hardenability

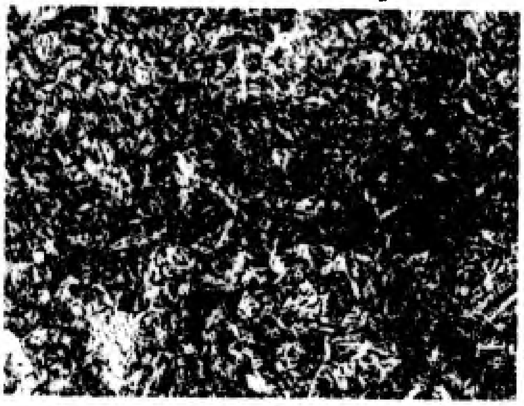
Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
47.5	5	7	12/16"	1"	1-2/16"	1-5/16"

Microstructure and Remarks

The steel having very poor hardenability, microstructure at the center of the section consists predominantly of tempered non-martensitic austenite decomposition products. The quantity of these products midway between the surface and center is appreciably less than at the center but is still large. The ballistic shock failure of the plate correlates with the microstructure.

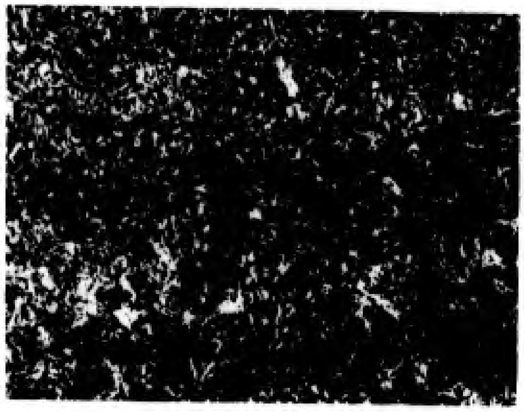
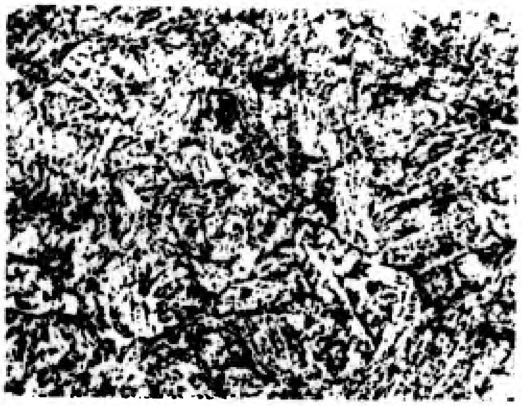
The plate was so badly laminated throughout the section that the impact properties of the material cannot be determined from the V-notch Charpy tests or the fibre fracture test. This extreme unsoundness was reflected in the PTP test by the failure of all the plates of the series at -12°F and -15°F even though the projectile was only undermatching.

Carnegie-Illinois 2" Plate No. TB-143317
(Microspecimen etched with 4% Picral)



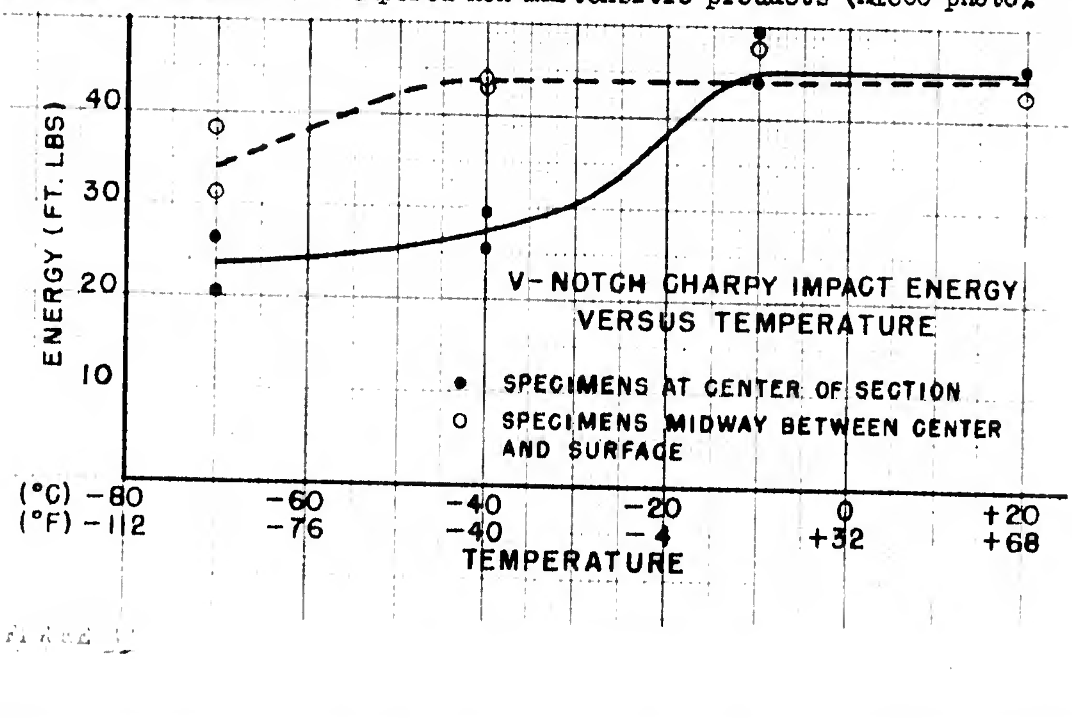

X200 **Center of Section** X1000

Moderate banding - A fairly large amount of tempered non-martensitic products is present in the light-etching bands (X1000 photo.).

X200 **Midway Between Surface and Center** X1000

Slight banding - The light etching bands contain tempered martensite and a small amount of tempered non-martensitic products (X1000 photo).



DATA SHEET NO. 15

Carnegie-Illinois Steel Corp.

Heat No. 15378 Plate No. TB-143317 Thickness 2.02"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.26	1.09	.18	.022	.015	.96	.58	.36	-	-
Watertown Arsenal	.26	1.08	.23	.024	.014	1.02	.57	.34	.06	.03

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1544	2	1	Water
1022	3-3/4	2	Water

Physical Properties Reported

T.S.	151,300	% R.A.	56.3
Y.P.	138,700	Izod	--
% Elong.	17.5	Brinell	311

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-30°F.	75 mm T21 Slug	1502(-8)	Passed: No cracking.	37 mm APC M51	Failed: 3"x3-1/8"B.S.

In this heat: 0 plates of 4 failed shock. (Passed -25°F, -25°F, -29°F, and -30°F (no cracking).) 2 of 4 plates failed PTP. (Failed -29°F and -30°F (by excessive B.S.). Passed -25°F (borderline B.S.) and -25°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
302	302	297	B	B	Mixed (10% Cryst.)	Mixed (Trace Cryst.)	Mixed (25% Cryst.)

Macrostructure and Microscopic Inclusion Determination

Macrostructures are similar in both rolling directions. Both macroscopic and microscopic examination of inclusions indicated that the armor is clean and free from long stringers.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
48.5	7	9	1-2/16"	1-5/16"	1-7/16"	1-12/16"

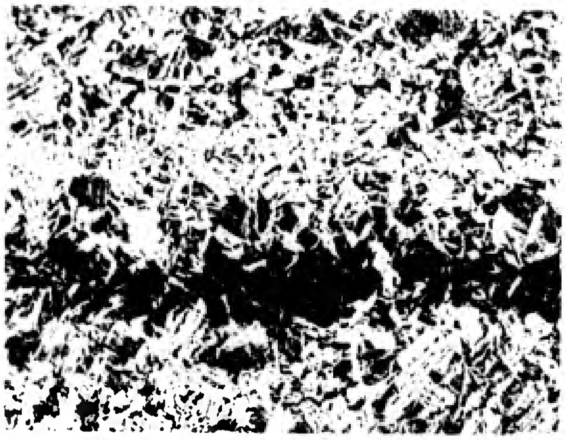
Microstructure and Remarks

In approximately one third of the banded structure at the center of the section, bands containing a fairly large amount of tempered austenite decomposition products other than martensite are present. The structure in the balance of the bands here and the structure midway between the center and the surface consist of tempered martensite plus only a small amount of tempered non-martensitic products. The scarcity of the latter constituent is due to very efficient quenching, for hardenability of the steel is inadequate even by the Rc 43 criterion.

Microscopic determination of the microstructure is corroborated by the V-notch Charpy tests; the material at the center of the section shows a drop in impact energy at -40°C, whereas the room temperature Charpy value of the armor midway between center and surface persists down to past -40°C and is equal to that of similar material that is known to have been completely quench hardened. Midway Charpy properties being excellent, the fibre fracture is only 25% crystalline and all plates of the series successfully resisted the slug.

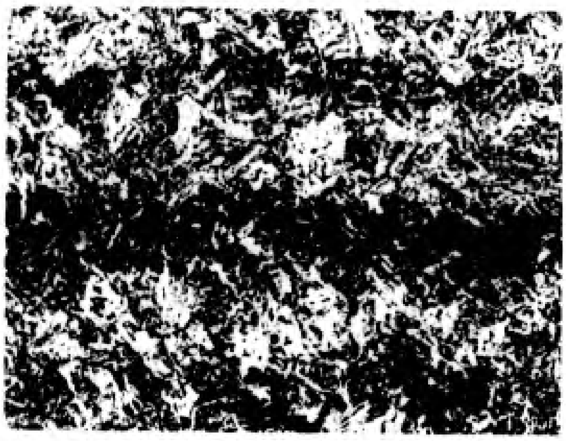
The behavior of the series when PTP tested illustrates again the effect of decrease in temperature upon spalling occurrence. Since no long stringers were detected in the sample examined, the cause of the spalling is apparently the 300 Brinell hardness.

Standard (Great Lakes) 2" Plate No. 1X4
(Microspecimen etched with 4% Picral)



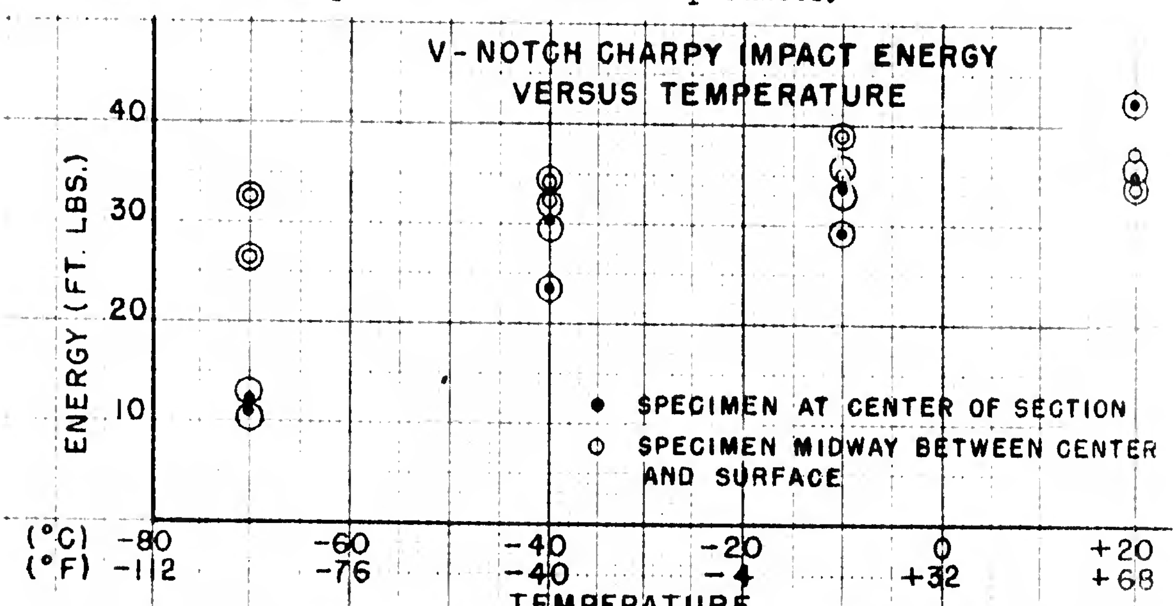
X200 **Center of Section** X1000

Moderate banding - Typical microstructure is largely tempered non-martensitic austenite decomposition products.



X200 **Midway Between Surface and Center** X1000

Some banding - Typical microstructure is tempered martensite and a large amount of tempered non-martensitic products.



NOTE: ⊙ AND ◎ SIGNIFY THAT CHARPY SPECIMEN FRACTURES CONTAIN DEEP LAMINATIONS

FIGURE 7?

DATA SHEET NO. 16

Standard Steel and Spring Co.
(Steel Supplied by Great Lakes Steel Corp.)

Heat No. GSG-635 | Plate No. 1X4 | Thickness 2.03"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Zr	Cu	Al
Company	.30	.83	.80	.026	.016	-	.61	.16	.08	-	-
Watertown Arsenal	.28	.85	.75	.021	.014	trace	.58	.17	.105	.09	.015

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1600		3-1/4	Water Spray
1160		3-1/4	Air

Physical Properties Reported

T.S.	123,000L, 123,500T
Y.P.	105,000L, 106,500T
% Elong.	19.0L, 14.0T
% R.A.	57.3L, 35.7T
Izod	-- --
Brinell	248-269

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-15°F.	75 mm T21 Slug	1519(+4)	Passed: No cracking.	37 mm APC M51	Failed: 3½x4" B.S.

In this heat: 2 plates of 4 failed shock. (Failed -15°F and -15°F (by excessive cracking). Passed -12°F and -15°F (no cracking).) 4 of 4 plates failed PTP. (Failed -12°F, -15°F, -15°F, and -15°F (by excessive B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
285 277	One Side 277 Other Side 248	235	E	E	Mixed (10% Cryst.)	Mixed (Trace Cryst.)	Mixed (50% Cryst.)

Macrostructure and Microscopic Inclusion Determination

The plate was straightaway rolled. Macrostructure checks the steel soundness fracture. Microscopic examination revealed that the "E" rating was due to oxide inclusions in many long stringers throughout the section. (The inclusion condition in this plate is identical to that in its companion plate No. 1X1.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
48.5	5	8	12/16"	1"	1-4/16"	1-8/16"

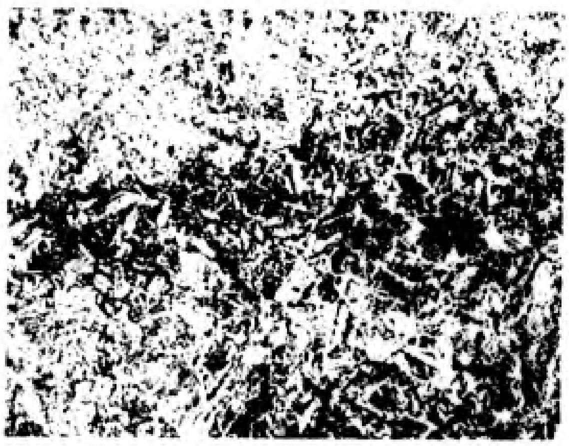
Microstructure and Remarks

Microstructure and V-notch Charpy impact results of this plate and its companion plate No. 1X1 (see Data Sheet No. 14) are similar. The fibre fracture of the subject plate being less laminated shows much more crystallinity (also since the fracture bar was notched at both faces in addition to the edges, the fracture area on which the 50% crystallinity is based is less than that of plate 1X1). In view of the similarity of microstructures of the two plates, it would be expected that ballistic shock behaviors would also have been similar—that the subject plate also would have failed to resist the slug. In the series two of four plates did fail the shock test.

Ford 2" Plate No. 2040-R
(Microspecimen etched with 4% Picral)

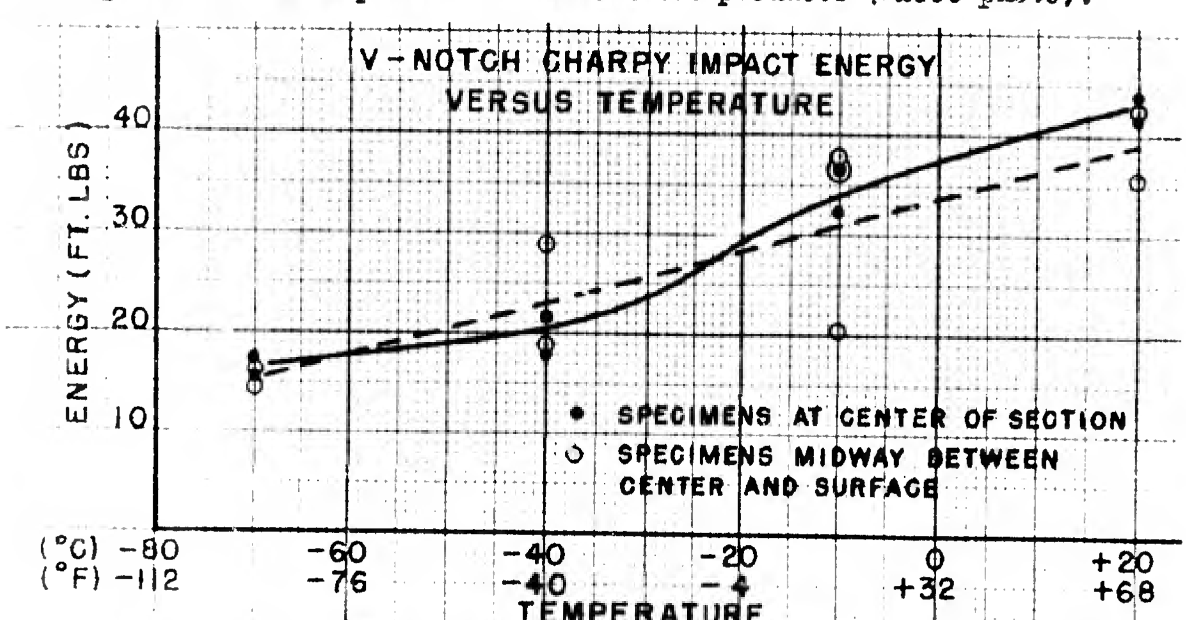
X200 **Center of Section** X1000

Severe banding - Microstructure of the light-etching bands is largely tempered non-martensitic products (X1000 photo).



X200 **Midway Between Surface and Center** X1000

Moderate banding - The light-etching matrix is tempered martensite plus a large amount of tempered non-martensitic products (X1000 photo).



NOTE: ⦿ SIGNIFIES THAT CHARPY SPECIMEN FRACTURE CONTAINS A DEEP LAMINATION

DATA SHEET NO. 17

Ford Motor Co.

Heat No. 9282E | Plate No. 2040-R | Thickness 1.98"

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.26	1.30	.25	.026	.020	.10	.55	.40	-	-
Watertown Arsenal	.30	1.37	.25	.026	.020	.10	.60	.41	.16	.02

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1650	2	4	Caustic
1100	2	6	Air

Physical Properties Reported

T.S.	128,000L, 128,200T
Y.P.	109,500L, 109,200T
% Elong.	20L, 17.5T
% R.A.	64L, 46.5T
Izod	81L, 40T
Brinell	277

Ballistic Properties

Temp.	Shock Proj.	Shock Vel. F/S	Shock Result	PTP Proj.	PTP Result
-26°F.	75 mm T21 Slug	1503(+13)	Passed: No cracking.	37 mm APC M51	Passed: 2-1/4x2-3/4".

In this heat: 0 plates of 3 failed shock. (Passed -25°F, -26°F, and -26°F (no cracking).) 0 plates of 3 failed PTP. (Passed -25°F, -26°F and -26°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating Long.	Steel Quality Fracture Rating Trans.	Fibre Fracture Slow Long.	Fibre Fracture Slow Trans.	Fibre Fracture Fast Long.
265	265	269	D	D Centerline	Mixed (25% Cryst.)	Mixed (5% Cryst.)	Mixed (60% Cryst.)

Macrostructure and Microscopic Inclusion Determination

The plate was straightaway rolled. The steel quality fracture "D" rating checks with the macrostructure. The stringers appear to be due to the concentrations of sulphides seen under the microscope at the center of the section.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Still Water (H=1)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop: Water Spray (H=1.8)	Plate Thickness Quenchable at Center to 400 BHN: Still Water (H=1)	Plate Thickness Quenchable at Center to 400 BHN: Water Spray (H=1.8)
53	8	11	1-4/16"	1-8/16"	1-12/16"	2-2/16"

Microstructure and Remarks

Comparison of microstructure with Jominy hardenability shows that in this inadequate hardenability material the occurrence of non-martensitic austenite decomposition products was further assisted by poor quenching efficiency. The quantity of these constituents is therefore large in the region midway between the plate surface and center as well as at the center. Accordingly, low temperature V-notch Charpy energy is poor at both testing locations and the fibre fracture shows much crystallinity.

Although the plate is characterized by low impact resistance, ballistic shock failures did not occur in the series. This is an indication that the ballistic shock test given to the 2" plates at Camp Shilo was too mild.

Similarly, although centerline concentrations of non-metallics were detected in the plate examined, no spalling was caused by the PTP penetrations in the case of all plates of the series. The need of a larger caliber projectile or obliquity firing in order to determine the low temperature resistance to spalling of 2" plate is thus indicated.

Chemical Analysis

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	Al
Company	.26	1.30	.25	.026	.020	.10	.55	.40	-	-
Watertown Arsenal	.30	1.37	.25	.026	.020	.10	.60	.41	.16	.02

Heat Treatment

Temp. °F.	Hrs. Rise	Hrs. Soak	Coolant
1650	2	4	Caustic
1100	2	6	Air

Physical Properties Reported

T.S.	128,000L, 128,200T
Y.P.	109,500L, 109,200T
% Elong.	20L, 17.5T
% R.A.	64L, 46.5T
Izod	81L, 40T
Brinell	277

Ballistic Properties

Temp.	Shock Proj.	Shock Vol. F/S	Shock Result	PTP Proj.	PTP Result
-26°F.	75 mm T21 Slug	1503(+13)	Passed: No cracking.	37 mm APC M51	Passed: 2-1/4x2-3/4".

In this heat: 0 plates of 3 failed shock.(Passed -25°F, -26°F, and -26°F (no cracking).) 0 plates of 3 failed PTP.(Passed -25°F, -26°F and -26°F (no B.S.).)

Hardness and Fracture Tests

BHN 1/4" from Surface	BHN Midway Surface - Center	BHN at Center	Steel Quality Fracture Rating		Fibre Fracture		
					Slow		Fast
			Long.	Trans.	Long.	Trans.	Long.
265	265	269	D Centerline	D	Mixed (25% Cryst.)	Mixed (5% Cryst.)	Mixed (60% Cryst.)

Macrostructure and Microscopic Inclusion Determination

The plate was straightaway rolled. The steel quality fracture "D" rating checks with the macrostructure. The stringers appear to be due to the concentrations of sulphides seen under the microscope at the center of the section.

Jominy Hardenability

Rc End Hardness at 1/16"	16ths to Beginning of Rc Drop	16ths to 43 Rc (400 BHN)	Plate Thickness Quenchable at Center to Hardness of Beginning of Jominy Drop		Plate Thickness Quenchable at Center to 400 BHN	
			Still Water (H=1)	Water Spray (H=1.8)	Still Water (H=1)	Water Spray (H=1.8)
53	8	11	1-4/16"	1-8/16"	1-12/16"	2-2/16"

Microstructure and Remarks

Comparison of microstructure with Jominy hardenability shows that in this inadequate hardenability material the occurrence of non-martensitic austenite decomposition products was further assisted by poor quenching efficiency. The quantity of these constituents is therefore large in the region midway between the plate surface and center as well as at the center. Accordingly, low temperature V-notch Charpy energy is poor at both testing locations and the fibre fracture shows much crystallinity.

Although the plate is characterized by low impact resistance, ballistic shock failures did not occur in the series. This is an indication that the ballistic shock test given to the 2" plates at Camp Shild was too mild.

Similarly, although centerline concentrations of non-metallics were detected in the plate examined, no spalling was caused by the PTP penetrations in the case of all plates of the series. The need of a larger caliber projectile or obliquity firing in order to determine the low temperature resistance to spalling of 2" plate is thus indicated.

APPENDIX A

Fracture Test Standards for
Soundness of
Rolled Homogeneous Armor Plate

Fracture Test Standards for

Soundness of

Rolled Homogeneous Armor Plate

Abstract of U. S. Army Ordnance Department Spec. AXS-488, Appendix I, 18 November 1943

The following descriptions of the standards shall be used in making decisions in borderline cases:

A Fracture: a. Devoid of visible laminations.

B Fracture: a. Small laminations present but well distributed and not concentrated in any one plane.

b. No lamination exceeding ½ T (thickness) in length.

C Fracture: a. Lamination or laminations present exceeding limits for B Fracture.

b. No single lamination exceeding 2T in length.

c. No single lamination exceeding 1½T in length in conjunction with another disconnected lamination in the same plane.

d. No lamination or laminations in any one plane with a total length exceeding 75 percent of the length of the fracture.

D Fracture: a. Lamination or laminations present exceeding limits for C fracture.

b. Continuous or essentially continuous laminations (total length of lamination or laminations in same plane exceeding 75 percent of length of fracture) in not more than three planes.

E Fracture: a. Continuous or essentially continuous laminations (total length of lamination or laminations in same plane exceeding 75 percent of length of fracture) in more than three planes.

ADDENDUM

B- Fracture: Between B and C fracture ratings.

C- Fracture: Between C and D fracture ratings.

Note: Plate 1/4 to 1-1/8 inches, inclusive, is designated as "acceptable" if the fracture is classified as "A", "B", or "C" and "rejectable" if the fracture is classified as "D" or "E". Plate 1-1/4 to 4 inches, inclusive, is designated as "acceptable" unless the fracture rating is "E".

APPENDIX 3

Tables Summarizing the Metallurgical Data
Supplied by the Manufacturers and the Low Temperature Ballistic Data of the
1", $1\frac{1}{2}$", and 2" Rolled Homogeneous Plates Tested at Camp Shilo

RESTRICTED

US AR

MANUFACTURER	HEAT NUMBER	PLATE NUMBER	THICKNESS	CHEMISTRY C	Mn	Si	S	P	Ni	Cr	Mo			QUENCH TEMP	HR. RISE	HRS SOAK	COOLANT	TEMP.
AMERICAN CAR & FOUNDRY	H-50164	R8B	1.04"	.25	.71	.22	.016	.016	1.27	.74	.46			1600			WATER	1180
" "	"	R8C	1.06"	"		"												
" "	"	R8D	1.02"	"														
" "	"	R8E	1.05"															
CARNEGIE-ILLINOIS STEEL CORP.	B-52607	42T1	1.02"	.27	.91	.21	.020	.020	1.05	[illegible]	.38			1544	1	[illegible]		[illegible]
" "	"	42T2	" "	"	"	"	"	"	"	"	"			"			"	"
" "	"	13T3	1.04"	"	"	"	"	"	"	"	"			"	"	"	"	"
" "	"	42T4	1.00"	"	"	"	"	"	"	"	"			"	"	"	"	"
HENRY DISSTON & SONS	3339	1	1.02"	.23	.51	.22	.015	.020	2.45	.21	.27			[illegible]	[illegible]	1	Water Spray	100
" "	"	2	" "	"	"	"	"	"	"	"	"			"	"	"	"	"
" "	"	4	" "	"	"	"	"	"	"	"	"			"	"	"	"	"
" "	"	5	1.01"	"	"	"	"	"	"	"	"			"	"	"	"	"
FORD MOTOR CO.	9297E	3223R	1.03"	.25	1.26	.24	.016	.016	.05	.53	.43			1650	1	3	PLATEN	
" "	"	3748R	1.00"	"	"	"	"	"	"	"	"			"	"	"	Water	"
" "	"	3748R	0.99"	"		"	"	"	"	"	"			"	"	"	"	"
" "	"	3749R	1.00"	"	"	"	"	"	"	"	"			"			"	"
REPUBLIC STEEL CORP.	RE12699	61	1.00"	.26	.87	.26	.018	.020	.86	.71	.54			1600			WATER SPRAY	112
" "	"	62	1.03"	"	"	"	"	"	"	"	"			"			"	"
" "	"	63	"	"	"	"	"	"	"	"	"			"			"	"
" "	"	64	1.01"	"	"	"	"		"	"	"			"			"	"
STANDARD STEEL SPRING CO.	DS6725	X1	1.06"	.28	.92	.81	.025	.020		.64	.17	ZR .09		1600	1/2	1/2	WATER	995
" "	"	X2	"	"	"	"	"	"		"	"	"		"	"	"	"	"
" "	"	X4	"	"	"	"	"	"		"	"	"		"	"	"	"	"
" "	"	X5	"	"	"	"	"	"		"	"	"		"	"	"	"	"
STANDARD STEEL SPRING CO.	DS7344	X54	1.02"	.25	1.55	.22	.014	.016			.42			1600	3/4	1/2	WATER	960
" "	"	X55	1.00"	"	"	"	"	"			"			"	"	"	"	"
" "	"	X56	1.02"	"	"	"	"	"			"			"	"	"	"	"
" "	"	X57	1.00"	"	"	"	"	"			"			"	"	"	"	"
STANDARD STEEL SPRING CO.	Y101	64	1.00"	.25	1.50	.18	.022	.015			.30			1600	1/2	1/2	WATER	900
" "	"	66	"	"	"	"	"	"			"			"	"	"	"	"
" "	"	67	"	"	"	"	"	"			"			"	"	"	"	"
" "	"	68	1.01"	"	"	"	"	"			"			"	"	"	"	"
[illegible] IRON WKS CO.	440297	1	1.02"	.26	.92	.20	.017	.014	1.24	1.03	.62							
" "	"	2	1.01"	"	"	"	"	"	"	"	"							
" "	"	3	"	"	"	"	"	"	"	"	"							
" "	"	4	1.00"	"	"	"	"	"	"	"	"							

1" ROLLED HOMOGENEOUS ARMOR
LOW TEMPERATURE BALLISTIC TESTS
U.S. ARMY - ORDNANCE PROVING CENTER - WINTER DETACHMENT - CAMP S

(C)HEMISTRY S	P	Ni	Cr	Mo		QUENCH TEMP.	HRS RISE	HRS SOAK	COOLANT	TEMPER TEMP.	HRS. RISE	HRS SOAK	COOL	TENSILE STRENGTH	YIELD POINT	% ELONG.	% R.A.	IZOD	BRINELL	PLATE TEMPERATURE
.016	.016	1.27	.74	.46		1600			WATER	1080			AIR						337-339	-18°F
						"			"	"			"						338-339	-19°F
						"			"	"			"						337-338	-27°F
						"			"	"			"						331-339	-27°F
.020	.020	1.03	.40	.38		1544	1	3/4	"	914	2 1/4	1	WATER	164000	154000	16.5	56.5		332	-18°F
"	"	"	"	"		"	"	"	"	"	"	"	"	"	"	"	"		"	-19°
"	"	"	"	"		"	"	"	"	"	"	"	"	"	"	"	"		"	-27°
"	"	"	"	"		"	"	"	"	"	"	"	"	"		"	"		"	"
.015	.020	2.45	.21	.27		1420	1 1/2	1	Water Spray	1000		3	AIR						331-341	-29°
		"		"		"	"	"	" "	"		"	"						341	-30°
		"		"		"	"	"	" "	"		"	"						341-352	-27°
		"		"		"	"	"	" "	"		"	"						293-311	-22°
.016	[illegible]	.65	.53	.43		1650	1	3	PLATEN WATER	"	1	4	"	145500 T 146300 L	132000 T 133500 L	14.0 T 18.0 L	20.0 T 56.0 L		302-321	-18°F
				"		"	"	"		"	"	"	"	"					311	"
		"		"		"	"	"	"	"	"	"	"	"	"	"	"		"	-29°
		"		"		"	"	"	"	"	"	"	"	"	"	"			"	"
.013	.020	.58	.71	.54		1600			WATER SPRAY	1125				123500	107000	17.0		51.9	321-341	-27°F
		"		"					" "	"				"	"	"		"	321-331	"
		"		"					" "	"				"	"	"		"	341	-19°F
		"		"					" "	"				"	"	"		"	321	-18°F
.025	.020		.64	.17	.28 .18	1600	1/2	1/2	WATER	975	1/2	2 1/2	AIR	147300 T 148000 L	137900 T 136000 L	13.5 16.0	43.2 37.9		321-337	-27°F
		"	"	"	"	"	"	"	"	"	"	"	"	"	"	"			329-336	"
		"	"	"	"	"	"	"	"	"	"	"	"	"	"	"			331-337	-19°F
		"	"	"	"	"	"	"	"	"	"	"	"	"	"	"			324-325	-18°F
.014	.016			.42		1600	3/4	1/2	WATER	960	1/2	2 1/2	AIR	156750 T 156500 L	144000 T 141000 L	16.5 T 13.5 L	52.0 T 56.0 L			-18°F
				"		"	"	"	"	"	"	"	"	"	"	"	"			-27°F
				"		"	"	"	"	"	"	"	"	"	"	"	"			-18°F
				"		"	"	"	"	"	"	"	"	"	"	"	"			28°F
.012	.015			.38		1600	1/2	1/2	WATER	900	1/2	2 1/2	AIR	153000 T 151000 L	141000 T 142000 L	13.5 T 17.5 L	49.2 T 44.9 L			-33°F
				"		"	"	"	"	"	"	"	"	"	"	"	"			30°F
				"		"	"	"	"	"	"	"	"	"	"	"	"			-29°F
																				-27°F
.017	.016	[illegible]	[illegible]	[illegible]															287-327	-34°F -16°F -9.5°F -30°F
																			" "	
																				-31°F
																			" "	"

2

WATERTOWN ARSENAL MARCH 12, 1943 SHEET 1 RESTRICTED

[illegible] CAMP SHILO, CANADA

PLATE TEMPERATURE	SHOCK TEST				PTP TEST	REMARKS
	PROJECTILE	SPEC. VELO.	ACTUAL VELOCITY	RESULT	37MM M51 APC	
[illegible]°F	37MM APC M51	1282	1265	1/2" CRACK ON HB.	1 3/4" X 2"	SATISFACTORY
[illegible]°F	" "	1298	1279	1" CRACK ON HB	2 3/4 X 2 1/4"	"
[illegible]°F	[illegible]	1266	1262	1 1/2" CRACK ON HB.	2" X 2 1/4"	"
[illegible]	[illegible]	1290	1277	1/2" CRACK ON HB.	2 3/4 X 2 13/16"	"
[illegible]	[illegible]	1266	1269	3" CRACK ON B.	1 3/4 X 1 3/4"	"
[illegible]	" "	"	1262	NO CRACKING	1 3/4 X 2 1/4"	"
[illegible]	"	1282	1299	FAILED CP-B.S. 1" X 1 1/4"	—	FAILED - B.S. ON SHOCK TEST
[illegible]	[illegible]	1250	1252	2" CIR. CRACK 1" CRACK ON BULGE	1 3/4" X 1 3/4" INC. B.S. 4 1/2" DIA	FAILED - INC. B.S. ON PTP TEST
[illegible]	"	1266	1271	CP-1 1/2 X 1" PUNCHING 2X3" B.S. FAILED	—	FAILED - B.S. ON SHOCK TEST
[illegible]	[illegible]	"	1273	CP-1/2 X 1" PUNCHING 1 3/4 X 1 3/16 B.S.	2 1/8 X 2 3/8" WITH B.S.	FAILED - B.S. ON SHOCK TEST
[illegible]	[illegible]	"	1281	CP-1" X 1 1/2" B.S.	2 1/8 X 1 9/16	FAILED - B.S. ON SHOCK TEST
[illegible]	[illegible]	1258	1290	CP-1/2 X 1/4 PUN. S.	1 7/8 X 2"	SATISFACTORY
[illegible]	[illegible]	1274	1259	1" CRACK ON BULGE	1 3/4" X 1 15/16"	SATISFACTORY
[illegible]	[illegible]	1250	1258	" " " L.B	1 5/8" X 1 7/8"	"
[illegible]	[illegible]	1242	1240	" " " "	1 7/8" X 2 1/8"	"
[illegible]	[illegible]	1250	1252	1 1/2" CIRCULAR CRACK	1 3/4" X 1 7/8"	"
[illegible]	[illegible]	"	1241	NO CRACKING	2" X 2 1/4"	SATISFACTORY
[illegible]	[illegible]	1274	1259	" "	1 13/16" X 2 1/8"	"
[illegible]	[illegible]	"	1272	" "	1 3/4" X 1 15/16"	"
[illegible]	[illegible]	1258	1278 1276	"	2" X 2 3/8"	"
[illegible]	[illegible]	1250	1266	1 1/2" CIR. CRACK ON BULGE	1 5/8" X 1 3/4"	SATISFACTORY
[illegible]	[illegible]	"	1252	1 1/2", 1/2", 1 1/4" CRACKS ON B	" " "	"
[illegible]	[illegible]	"	1270	CP 1 3/4" X 1 3/4" PUNCHING	" " "	FAILED
[illegible]	[illegible]	"	1265	2", 2" CRACKING	" " "	SATISFACTORY
[illegible]°F	"	1266	1293	NO CRACKING	1 3/4" X 1 7/8"	SATISFACTORY
[illegible]	"	1250	1242	" "	1 3/4" X 1 13/16"	"
[illegible]°F	"	1266	1260	" "	1 3/4" X 1 3/4"	"
[illegible]°F	"	1250	1245	1 1/2" CIRCULAR CRACK	1 5/8" X 5/8"	"
[illegible]°F	[illegible]	1250	1250	1 1/2" CIR. CRACK ON BULGE	1 5/8" X 1 5/8"	SATISFACTORY
[illegible]°F	"	"	1227	1 1/2" CRACK ON BULGE	1 3/4" X 1 13/16"	"
[illegible]°F	"	"	1291	1", 1 1/8" CRACKING	1 5/8" X 1 3/4"	"
[illegible]°F	"	1259	1174	1 1/2" HORIZONTAL CRACK	1 9/16" X 1 11/16"	"
-34°F	37MM APC M51	1266	1273	O.K. NO CRACKS	FAILED 3" X 4" W/B.S.	O.K. AT -16°F
-16°F	[illegible]	1266	1273	O.K. NO CRACKS	2 X 2 1/4"	FAILED AT -34°F BS ON PTP
[illegible]°F	[illegible]	1259	1264	" "	2 1/4" X 2 1/2"	SATISFACTORY
[illegible]°F	[illegible]	1259	1270	" "	1 9/16" X 1 3/4"	"
[illegible]°F	"	1259	1253	" "	1 9/16" X 1 3/4"	"
[illegible]	[illegible]	1250	1290	" "	1 3/4" X 1 3/4"	"

[illegible] PLATES TESTED IN ACCORDANCE WITH SPECIFICATION AXS-495, REVISION 1.

3

RESTRICTED

1½" ROLLED H
LOW TEMPERATU
U.S. ARMY - ORDNANCE PROVING CENTER

MANUFACTURER	HEAT NUMBER	PLATE NUMBER	THICKNESS	C	Mn	Si	S	P	Ni	Cr	Mo			QUENCH TEMP	QUENCH HRS RISE	QUENCH HRS SOAK	QUENCH COOLANT	TEMP. TEMP	TEMP. HRS [illegible]
American Car & Foundry	H-[illegible]	R12B	1.50"	.25	.77	.26	.016	.018	1.27	.78	.44			1600			WATER	1180	
"	"	R12C	1.50"	"	"	"	"	"	"	"				"					
"	"	R12D	1.54"	"	"	"	"	"	"	"	"			"				"	
"	"	R12E	1.51"	"	"	"	"	"	"	"	"			"					
"	RH307	307-1	1.51"	.26	.80	.27	.019	.018	.95	.71	.49								
"	"	307-9	1.48"	"	"	"	"	"	"	"	"							"	
"	J-301	J12-B	1.50"	.26	1.64	.23	.014	.015	-	-	.48			1625			WATER	1080	
"	"	J12C	1.50"	"	"	"	"	"			"			"					
"	"	J12D	1.50"	"	"	"	"	"						"			"		
"	"	J12E	1.50"	"	"	"	"	"			"								
[illegible] Tubing Steel Corp.	72345	[illegible]	1.50"	.27	1.04	.21	.023	.018	1.00	.57	.38			1544	1½	¾	WATER	1040	
"	"	"	1.50"	"	"	"	"	"	"	"	"								
"	"	"	1.50"	"	"	"	"	"	"	"	"								
"	"	"	1.51"	"	"	"	"	"	"	"	"								
"	"	"	1.50"	"	"	"	"	"	"	"	"			"			"		
[illegible] Steel, Inc.	22851	1	1.54"	.21	.50	.25	.012	.014	3.10	.04	.29	Cu .20		1425	½	2	WATER SPRAY	1100	
"	"	2	1.51"	"	"	"	"	"	"			"						"	
"	"	3	1.50"	"	"	"	"	"	"			"						"	
"	"	4	1.52"	"	"	"	"	"	"			"		"				"	
"	"	5	1.50"	"	"	"	"	"	"	"								"	
[illegible] Company	72996	3291R	1.50"	.26	1.32	.22	.019	.018	.16	.50	.47			1650	1½	1½	WATER	1080	
"	"	3292R	1.52"	"	"	"	"	"	"	"	"			"					
"	"	"	1.49"	"	"	"	"	"	"	"	"								
"	"	"	1.49"	"	"	"	"	"	"	"	"								
Geneva Steel Corp.	RH-[illegible]	-	1.52"	.27	.80	.27	.019	.018	.95	.71	.49			1600			WATER	1600	
"	[illegible]	-	1.50"	"	"	"	"	"	"	"	"						"	"	
"	"	-	1.51"	"	"	"	"	"	"	"									
"	"	-	1.48"	"	"	"	"	"	"										
Standard Steel Spring Co.	GSG-924	1X1	1.49"	.29	.89	.68	.030	.030	-	.61	.16		Zr .08	1600		2¾	WATER SPRAY	1170	
"	"	1X2	1.48"	"	"	"	"	"		"	"		"	"				"	
"	"	1X3	1.49"	"	"	"	"	"		"	"			"					
"	"	1X4	1.51"	"	"	"	"	"		"									
"	"	1X5	1.50"	"	"	"	"	"		"	"			"					
Standard Steel Spring Co.	GSJ-335	M1X1	1.50"	.27	1.59	.25	.016	.021	-	-	.41								
"	"	M1X2	1.52"	"	"	"	"	"											
"	"	M1X3	1.51"	"	"	"	"	"											
"	"	M1X4	1.51"	"	"	"	"	"			"								
Standard Steel Spring Co.	GSY-75-10	1X1	1.51"	.27	1.86	.19	.022	.037	.05	-	.38			1600		2¾	WATER SPRAY	1170	
"	"	1X2	1.50"	"	"	"	"	"	"		"			"			"		
"	"	1X4	1.49"	"	"	"	"	"	"										
"	"	1X5	1.51"	"	"	"	"	"	"		"								
[illegible] Iron Works Co.	H-[illegible]	1	1.54"	.26	.92	.26	.024	.016	1.21	1.05	.66								
"	"	2	1.53"	"	"	"	"	"	"	"	"								
"	"	3	1.53"	"	"	"	"	"	"	"	"								
"	"	4	1.55"	"	"	"	"	"	"	"	"								
"	"	5	1.54"	"	"	"	"	"	"	"									

CTED

1½" ROLLED HOMOGENEOUS ARMOR

LOW TEMPERATURE BALLISTIC TESTS

U.S. ARMY – ORDNANCE PROVING CENTER – WINTER DETACHMENT – CAM[illegible]

HEAT NUMBER	PLATE NUMBER	THICK-NESS	CHEMISTRY C	Mn	Si	S	P	Ni	Cr	Mo			QUENCH TEMP	HRS RISE	HRS SOAK	COOLANT	TEMPER TEMP	HRS RISE	HRS SOAK	COOL	TENSILE STRENGTH	YIELD POINT
[illegible]	[illegible]	1.53"	.25	.77	.26	.016	.018	1.27	.78	.44			1600			WATER	1180			AIR		
	[illegible]	1.53"	"		"	"	"	"	"				"									
	[illegible]	1.54"	"		"	"	"	"	"				"									
	[illegible]	1.51"	"		"	"	"	"	"	"			"									
[illegible]	[illegible]	1.57"	.26	.80	.27	.019	.018	.95	.71	.49											119500	103[illegible]
	[illegible]	[illegible]				"	"	"	"	"			"									
[illegible]	[illegible]	1.52"	.26	1.64	.23	.014	.015	–	–	.48			1625			WATER	1080			AIR		
	[illegible]	[illegible]					"			"			"			"						
	[illegible]	[illegible]				"	"			"			"			"						
	[illegible]	[illegible]				"				"			"			"						
[illegible]	[illegible]	1.51"	.27	1.04	.21	.023	.018	1.00	.57	.38			1544	1½	¾	WATER	1040	2¾	1¼	WATER	143000	1[illegible]
		1.51"				"	"	"	"	"			"			"	"			"		
		1.53"				"	"	"	"	"			"			"	"					
		1.51"				"	"	"	"	"			"			"	"			"		
		1.53"				"	"	"		"			"			"						
[illegible]	[illegible]	[illegible]	.24	[illegible]	.25	.012	.014	3.10	.04	.29	Cu .20		1425	1½	2	WATER SPRAY	1100		2	AIR		
	[illegible]	[illegible]				"	"	"	"	"	"		"			"	"			"		
	[illegible]	[illegible]				"	"	"	"	"	"		"			"	"			"		
	[illegible]	[illegible]				"	"	"	"	"	"		"			"	"			"		
	[illegible]	[illegible]				"	"	"	"	"	"		"			"	"			"		
[illegible]	[illegible]	[illegible]	.24	1.32	.22	.019	.018	.16	.50	.47			1650	1½	3½	WATER	1080	2	6	AIR	L 132660 T 132000	11[illegible] 11[illegible]
	[illegible]	[illegible]					"	"	"	"			"							"		
		1.57"					"	"	"	"			"			"	"					
		1.57"				"	"	"	"	"			"			"	"					
[illegible]		1.53"	.27	.80	.27	.019	.018	.95	.71	.49			1600			WATER	1600			AIR	119500	1[illegible]
		1.50"	"	"	"	"	"	"	"	"						"	"			"		
		1.51"		"	"	"	"	"	"				"							"		
		1.49"		"	"	"	"	"	"							"						
[illegible]	[illegible]	1.49"	.29	.99	.68	.030	.030	–	.61	.16		Zr .08	1600		2¾	WATER SPRAY	1170		2¾	AIR	L 118700 T 119600	10[illegible] 103[illegible]
[illegible]	[illegible]	1.49"	"		"	"	"		"	"		"	"									
	[illegible]	1.49"	"		"	"			"	"		"										
	[illegible]	1.51"	"		"	"			"	"		"										
	[illegible]	1.50"	"		"	"	"		"	"		"										
[illegible]	[illegible]	1.50"	.27	1.59	.25	.016	.021	–	–	.41											L 138000 T 13[illegible]500	12[illegible] 12[illegible]
335	MIX2	1.52"	"	"																		
	MIX3	1.51"	"	"	"	"	"															
	MIX4	1.51"	"	"	"	"	"															
[illegible]	[illegible]	1.51"	.27	1.86	.19	.022	.037	.05	–	.38			1600		2¾	WATER SPRAY	1170		2¾	AIR	L 122200 T 123200	10[illegible] 10[illegible]
	[illegible]	1.50"	"	"	"	"	"	"					"			"						
	[illegible]	1.49"	"	"	"	"	"	"					"									
	[illegible]	1.51"	"	"	"	"	"	"		"			"									
[illegible]	[illegible]	1.54"	.26	.92	.26	.024	.016	1.21	1.05	.66												
	[illegible]	1.53"	"	"	"	"	"	"	"	"												
	[illegible]	1.53"	"	"	"	"	"	"	"	"												
	[illegible]	1.55"	"	"	"	"	"	"	"	"												
	[illegible]	1.54"	"	"	"	"	"	"	"	"												

NOTE: [illegible]

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1½" Rolled Homogeneous Armor

Low Temperature Ballistic Tests

Army-Ordnance Proving Center - Winter Detachment - Camp Shilo, Canada

Watertown

	Quench Temp.	Quench Hrs. Rise	Quench Hrs. Soak	Coolant	Temper Temp.	Temper Hrs. Rise	Temper Hrs. Soak	Cool	Tensile Strength	Yield Point	% Elong.	% RA	Izod	Brinell Hardness	Plate Temperature	Projectile	Shock Test Spec. Velk.
	1600			Water	1180			Air						267-268	-19°F	75mm T21 Slug	1250
				"	"									268-272	-16°F		1250
				"	"									263-269	-34°F		1272
				"	-									263-269	-34°F		1255
					"				119500	103000	17.0	23.9	47	255-269	-33°F		1255
					"									255-262	-34°F		1234
	1625			Water	1080			Air						283-284	-35°F		1250
								"						283-284	-35°F		1250
														284-284	-16°F		1250
														294-300	-16°F		1250
	1544	1½	¾	Water	1040	2¼	1¼	Water	143000	129000	20.5	65.0		293	-24°F	75mm T21 Slug	1250
					"			"						293	-25.3°F		1250
					"			"						293	-34°F		1250
					"			"						293	-34°F		1258
					"			"						293	-35°F		1250
[illegible]	[illegible]	1½	2	Water Spray	1100		2	Air						269-293	-14°F	75mm T21 Slug	[illegible]
					"			"						255-269	-25.5°F		1263
					"			"						255-293	-11.5°F	———	BL
					"			"						248-262	-25.6°F	75mm T21 Slug	1246
					"			"						248-262	-25.3°F		1250
	1550	1½	3½	Water	1080	2	6	Air	L 132660	114950	22	65.5	88	262	-22°F	75mm T21 Slug	1250
				"				"	T 132000	114000	17	47	88	255	-23°F		1266
				"										255	-32°F		1242
														255	-32°F		1242
	[illegible]			Water	1200			Air	119500	103000	17.0	23.9	47	255-269	-23°F	75mm T21 Slug	[illegible]
				"	"			"						255-262	-24°F		[illegible]
				"	"			"						255-269	-33°F		1255
														255-262	-34°F		1234
58	[illegible]		2¾	Water Spray	1170		2¾	Air	L 118700	106000	17.5	54.3		269-286	-17°F	75mm 25° APC M61	[illegible]
				"	"		"	"	T 119600	103000	16.5	46.0		255-268	-22°F	75mm T21 Slug	1234
				"	"		"	"						269-286	-17°F	75mm 25° APC M61	
				"	"		"	"						255-286	-22°F	75mm T21 Slug	
				"	"		"	"						248-286	-18°F		
									L 138000	129100	18.0	62.4		277-286	-29°F	75mm T21 Slug	
									T 137500	128100	18.5	62.8		269-286	-18.5°F		
														255-286	-30°F		
														255-277	-18.5°F		
	[illegible]		2¾	Water Spray	1170		2¾	Air	L 122200	100500	21.0	69.1		255-269	-18.5°F	75mm T21 Slug	
									T 123200	106600	18.0	52.2		248-262	-31°F		
														255-262	-33°F		
					"									255-269	-16.5°F		
															-14.5°F	75mm [illegible]	
															-16.5°		
														242-282	-25°F		
														242-282	-30°F		
														242-282	-28°F		

Note: Plates tested in accordance w[illegible]

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[illegible]	[illegible]	Plate Temperature	Shock Test: Projectile	Spec. Velocity	Actual Velocity	Result	PTP Test 37mm M51 APC	Remarks
[illegible]	[illegible]	-19°F	75mm T21 Slug	1250	1249	No Cracking	2 3/4 x 2 5/8 in B.S.	Satisfactory
[illegible]	[illegible]	-16°F		1250	Est. 1250	No Cracking	2 3/4 x 2 1/16"	"
[illegible]	[illegible]	[illegible]		1272	Est. 1272	No Cracking	2 3/4 x 2 1/2"	
[illegible]	[illegible]	[illegible]		1255	1252	No Cracking	2 3/4 x 2 1/2"	
[illegible]	[illegible]	[illegible]		1255	1250	No Cracking	2 1/2 x 3" B.S. - Borderline	OK - B.S. Tendencies
[illegible]	[illegible]	[illegible]		1234	1229	No Cracking	B.S. 3 1/4 x 3 1/4"	Failed - Back Spall
[illegible]	[illegible]	[illegible]		1250	1247	No Cracking	2 1/2 x 2 1/2"	Satisfactory
[illegible]	[illegible]	[illegible]		1250	1295	No Cracking	2 3/4 x 2 3/4"	"
[illegible]	[illegible]	[illegible]		1250	1250	No Cracking	2 1/2 x 2 1/2"	"
[illegible]	[illegible]	[illegible]		1250	1247	No Cracking	2 1/2 x 2 1/2"	"
[illegible]	[illegible]	[illegible]	[illegible] Slug	1250	1250	No Cracking	2 3/4 x 2 3/4" with B.S.	Satisfactory
[illegible]	[illegible]	[illegible]		1250	1302	No Cracking	2 3/4 x 3" with B.S.	OK - Borderline on B.S.
[illegible]	[illegible]	[illegible]		1250	1250	No Cracking	2 3/4 x 3" with B.S.	OK - Borderline on B.S.
[illegible]	[illegible]	[illegible]		1258	1261	CP - B.S. 5 1/4 x 7 3/4"	—	Failed Shock - CP & B.S.
[illegible]	[illegible]	[illegible]		1250	1249	No Cracking	2 3/4 x 3" with B.S.	OK - Borderline on B.S.
[illegible]	[illegible]	[illegible]	[illegible]	1282	1282	No Cracking	2 3/4 x 2 1/2"	Satisfactory 2nd Shock Rd. Developed Cracks
[illegible]	[illegible]	[illegible]		1258	1261	Cracks 19", 17", 6", 7", 2 1/2"	—	Failed - Excessive Cracks
[illegible]	[illegible]	[illegible]	B.L. 37mm M51 APC - 1597 F/S - Spec. 1500				2 1/2 x 2 3/4"	B.L. 97 F/S Excess
[illegible]	[illegible]	[illegible]	[illegible] Slug	1266	1264	CP - Cracks 22", 14", 10", 6"	—	Failed - Excessive Cracks
[illegible]	[illegible]	[illegible]		1250	1255	No Cracking	2 1/16 x 2 3/4"	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible] Slug	1250	1252	No Cracking	2 1/4 x 2 1/2"	Satisfactory
[illegible]	[illegible]	[illegible]		1266	1250	No Cracking	2 3/4 x 2 1/2"	
[illegible]	[illegible]	[illegible]		1242	1242	No Cracking	2 1/4 x 2 1/2"	"
[illegible]	[illegible]	[illegible]		1242	1239	No Cracking	2 1/4 x 2 1/2"	"
[illegible]	[illegible]	[illegible]	75mm T21 Slug	1266	Est. 1266	No Cracking	2 1/4 x 2 3/4"	Satisfactory
[illegible]	[illegible]	[illegible]		1250	1296	No Cracking	2 1/2 x 2 1/2"	"
[illegible]	[illegible]	[illegible]		1255	1250	No Cracking	2 1/4 x 2 3/4" with B.S.	
[illegible]	[illegible]	[illegible]		1234	1229	No Cracking	3 1/4 x 3 1/4" with B.S.	Failed - Excessive B.S.
[illegible]	[illegible]	[illegible]	75mm 2 1/2° APC M61	946	928	No Cracking	2 1/4 x 2 1/2"	OK - AP Shock Test
[illegible]	[illegible]	[illegible]	75mm T21 Slug	1234	1253	Broke - 3 Pc's	—	Failed - Shattered
[illegible]	[illegible]	[illegible]	75mm 2 1/2° APC M61	950	926	No Cracking	2 1/16 x 2 1/2"	OK - AP Shock Test
[illegible]	[illegible]	[illegible]	75mm T21 Slug	1255	1250	Broke - 3 Pc's	—	Failed Shattered
[illegible]	[illegible]	-19°F		1250	1249	Broke 2 Pc's & 9" x 9 3/4" B.S.	—	Failed - Shattered & B.S.
[illegible]	[illegible]	-29°F	75mm T21 Slug	1250	1248	No Cracking	2 1/4 x 2 7/16"	Satisfactory
[illegible]	[illegible]	[illegible]		1266	1264	No Cracking	2 1/4 x 2 3/8"	
[illegible]	[illegible]	-30°F		1255	1247	No Cracking	2 1/4 x 2 7/16	
[illegible]	[illegible]	-18.5°F		1258	1333	No Cracking	2 1/4 x 2 1/4"	
[illegible]	[illegible]	-18.5°F	75mm T21 Slug	1258	1311	No Cracking	2 3/4 x 2 1/2"	Satisfactory
[illegible]	[illegible]	-31°F		1280	1319 1269	No Cracking " "	2 1/4 x 2 1/2"	
[illegible]	[illegible]	[illegible]		1242	1211	No Cracking	2" x 2 1/4"	"
[illegible]	[illegible]	[illegible]		1258	1265	No Cracking	2 1/4 x 2 3/4"	
[illegible]	[illegible]	[illegible]	75mm T21 Slug	1282	1330 1381	No Cracking	2 1/2 x 2 5/8"	Satisfactory
[illegible]	[illegible]	[illegible]		1224	1278	No Cracking	2 x 2 1/2"	"
[illegible]	[illegible]	[illegible]		1265	1269	No Cracking	2 3/4 x 2 1/2"	"
[illegible]	[illegible]	[illegible]		1275	1260	No Cracking	2" x 2 5/16"	
[illegible]	[illegible]	[illegible]		1270	1272	No Cracking	2" x 2 3/4"	"

[illegible] with Specification AXS-488

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RESTRICTED

[illegible]	Heat No.	Plate Number	Thickness	C	Mn	Si	S	P	Ni	Cr	Mo	
								CHEMISTRY				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.014	.015	1.22	.72	.43	

RESTRICTED

2" R[illegible]
LOW TEM[illegible]

U.S. ARMY - ORDNANCE PROVING [illegible]

CHEMISTRY							QUENCH				TEMPER			
S	P	Ni	Cr	Mo			TEMP.	HRS. RISE	HRS. SOAK	COOLANT	TEMP.	HRS. RISE	HRS. SOAK	COOL
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]			WATER	1180			AIR
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	6	AIR
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	WATER	[illegible]	2	6	AIR
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			AIR
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	AIR

[illegible]

[illegible] Temperature Ballistic Tests

[illegible] Center - Winter Detachment - Camp Shilo, Canada

	Tensile Strength	Yield Point	% Elong.	% R.A.	Izod	Brinell Hardness	Plate Temperature	Project[illegible]
[illegible]						284	-26°F	75mm T21[illegible]
						284	-25°F	
						[illegible]-277	-30°F	
						[illegible]	-28°F	
						[illegible]	[illegible]	75mm T2[illegible]
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	[illegible]
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	[illegible]	75mm T2[illegible]
						[illegible]	[illegible]	75mm T2[illegible]
						[illegible]	[illegible]	
						[illegible]	[illegible]	
						[illegible]	-30°F	
						[illegible]	[illegible]	75mm T2[illegible]
						[illegible]	[illegible]	
						248-269	-15°F	
						248-269	-15°F	

Note: Plates tested in accordance with [illegible]

3

Shock Test			RTP Test	Remarks
Striking Velocity		Result	37mm M51 APC	
[illegible]	[illegible]	No Cracking	[illegible]	Satisfactory
[illegible]	[illegible]	No Cracking	[illegible]	OK Borderline [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible]	OK Borderline [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible]	Satisfactory
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]