File

OTTAWA December 21st, 1943.

REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1541.

Statistical Analysis and Correlation Study of the Metallurgical Properties of 1½-in. Armour Plate.

(Copy No. 14.)

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Abstract

Eighty-three (83) samples of $1\frac{1}{2}$-in. rolled armour plate were received for examination, together with ballistic and metallurgical reports.

The accuracy of ballistic limit tests varies from $\pm$ 10 to $\pm$ 35 feet per second.

The nature and extent of variation of ballistic and metallurgical tests and results are described graphically. The correlation between ballistic and some chemical and physical tests is proven to exist.

Variation in through-plate tensile properties, "n" values, inclusion ratings, decarburization, grain size, and microstructure are depicted graphically. It is pointed out that process levels were shifted several times during the period of investigation.

Through-plate reduction in area is shown to correlate with ballistic properties.

Deeper decarburization is shown to coincide with higher ballistic limits.

Cracking on the back of the armour is shown to be correlated with inclusion rating.

Grain size and microstructure are found to be very closely controlled. This indicates that melting method and deoxidation practice have been consistent.

Bureau of Mines
Division of Metallic
Minerals.
-
Ore Dressing
and Metallurgical
Laboratories

CANADA

DEPARTMENT
OF
MINES AND RESOURCES

Mines and Geology Branch

OTTAWA December 21st, 1943.

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SECTION ONE. - INTRODUCTION.

When an industrial process is in operation, as a rule the experimental method of research cannot be used, because usually the many variables of the process cannot be maintained constant while one variable is altered. It therefore becomes necessary to find out the effect of one variable on quality even though all the other variables are varying within

(Introduction, cont'd) -

their usual limits. The idea that such a procedure was possible was mentioned by Karl Daeves around 1924.

A considerable number of the large industries in the U.S.A., Canada and Great Britain are using statistical procedures to study their own operations. Information of practical value is to be found in the test records of war materials. This report gives information available in routine ballistic reports of 1½-in. armour plate.

Origin of Project and Purpose of Investigation:

This report is a part of the 1943 research work on armour plate undertaken by the Physical Metallurgy Research Laboratories of the Bureau of Mines. Samples were obtained through the assistance of Dr. C. W. Drury, Director of Metallurgy, Army Engineering Design Branch, Department of Munitions and Supply, Ottawa, Ontario, and Mr. H. L. Batten, T.O., for A.D. Tech(M), Inspection Board of United Kingdom and Canada, Ottawa, Ontario. Data supplied for 1½-in. Dominion Foundries and Steel rolled armour plate, including chemical analysis and physical and ballistic test results, were used in the present investigation.

Additional metallurgical tests on the above samples were made in these Laboratories.

SECTION TWO. - Variation in Chemical and Physical Properties of 1½-in. Armour Plate.

Origin of Data:

The ballistic reports on Plates R-1 to R-83 included chemical and physical test results. These results were placed in groups of 4 (See Appendix A).

Method of Presenting Data:

The method of obtaining a graphic picture of a manufacturing process, recommended by the American Society for Testing Materials, is the Quality Control Chart.

The tests were placed in groups of four and the average and range of each group were plotted. The control limits on the chart indicate the limits which are characteristic for the process. If a value exceeds the control limits it is a certain proof that there was present an assignable cause for that variation. The control limits are generally used as indication of the need for corrective action.

A controlled process will have test results which fluctuate above and below the average so frequently that runs of six or more consecutive values above or below average rarely occur. A run of six or more, therefore, is indicative that the process average has shifted. In 20 groups the normal expectancy is 12 runs. On each of the charts the number of runs is indicated.

(Four charts, Figures 1 to 4)
(constitute Pages 5 to 8.)
(Comments on charts appear)
(on next page.)

Comments on Charts (Figures 1 to 4):

In the case of manganese, the first twelve average values fall below the general average for the process. This is sufficient evidence to prove that the average manganese was deliberately shifted at or about Group 12. Vertical lines on the control charts indicate the approximate times the changes were made in the metallurgical process.

The alloy content of the steel was reduced at about Group 9. This reduced the hardenability of the steel from an average Grossman value of 9 to an average Grossman value of 8.

The chart for Izod impact values illustrates very clearly that 3 different heat-treating methods were used during this period. The first method took in approximately Groups 1-9; the second, Groups 10-14; and the third, Groups 15 and on.

It is interesting to notice that runs in the metallurgical properties coincide with runs in the ballistic properties.

Face damage, back damage, and ballistic limit are below average from Group 14 to Groups 20 (see Report of Investigation No. 1537, Figures 4, 6 and 2). Metallurgical tests that coincide with this run of low quality are:

Above Average	Below Average
Carbon	Molybdenum
Manganese	Chromium
Elongation	Yield
Izod	Hardness
	Hardenability

A guess as to why the ballistic properties dropped off is that the reduction in hardenability was not offset by a change in heat treatment and that, therefore, softer plate was made.

FIG. 1

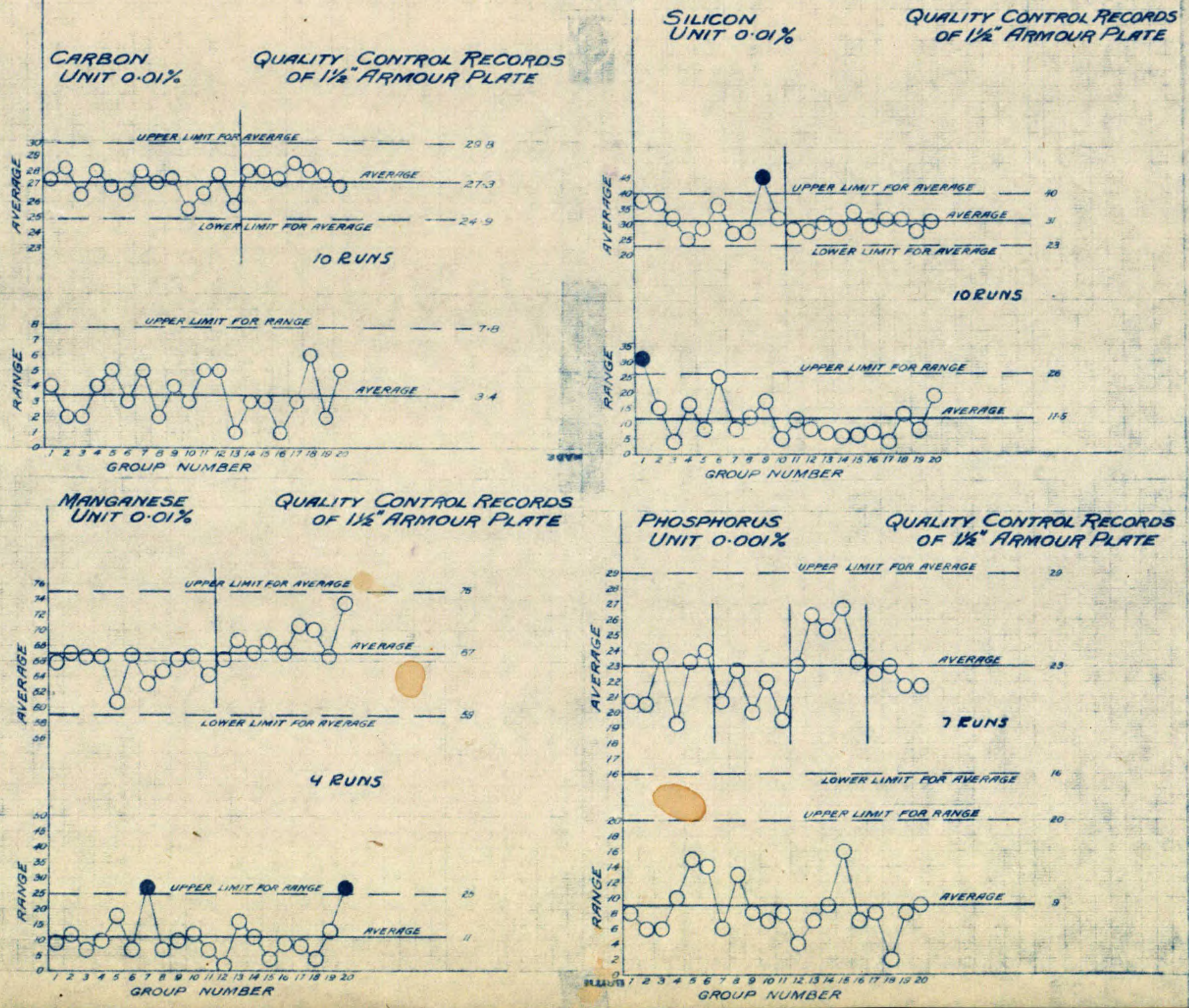

CARBON
UNIT 0·01%
QUALITY CONTROL RECORDS OF 1½" ARMOUR PLATE
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
29·8
27·3
24·9
10 RUNS
UPPER LIMIT FOR RANGE
7·8
3·4
GROUP NUMBER
SILICON
UNIT 0·01%
QUALITY CONTROL RECORDS OF 1½" ARMOUR PLATE
40
31
23
10 RUNS
26
11·5
MANGANESE
UNIT 0·01%
QUALITY CONTROL RECORDS OF 1½" ARMOUR PLATE
75
67
59
4 RUNS
25
11
PHOSPHORUS
UNIT 0·001%
QUALITY CONTROL RECORDS OF 1½" ARMOUR PLATE
29
23
16
7 RUNS
20
9
AVERAGE
RANGE

FIG. 2

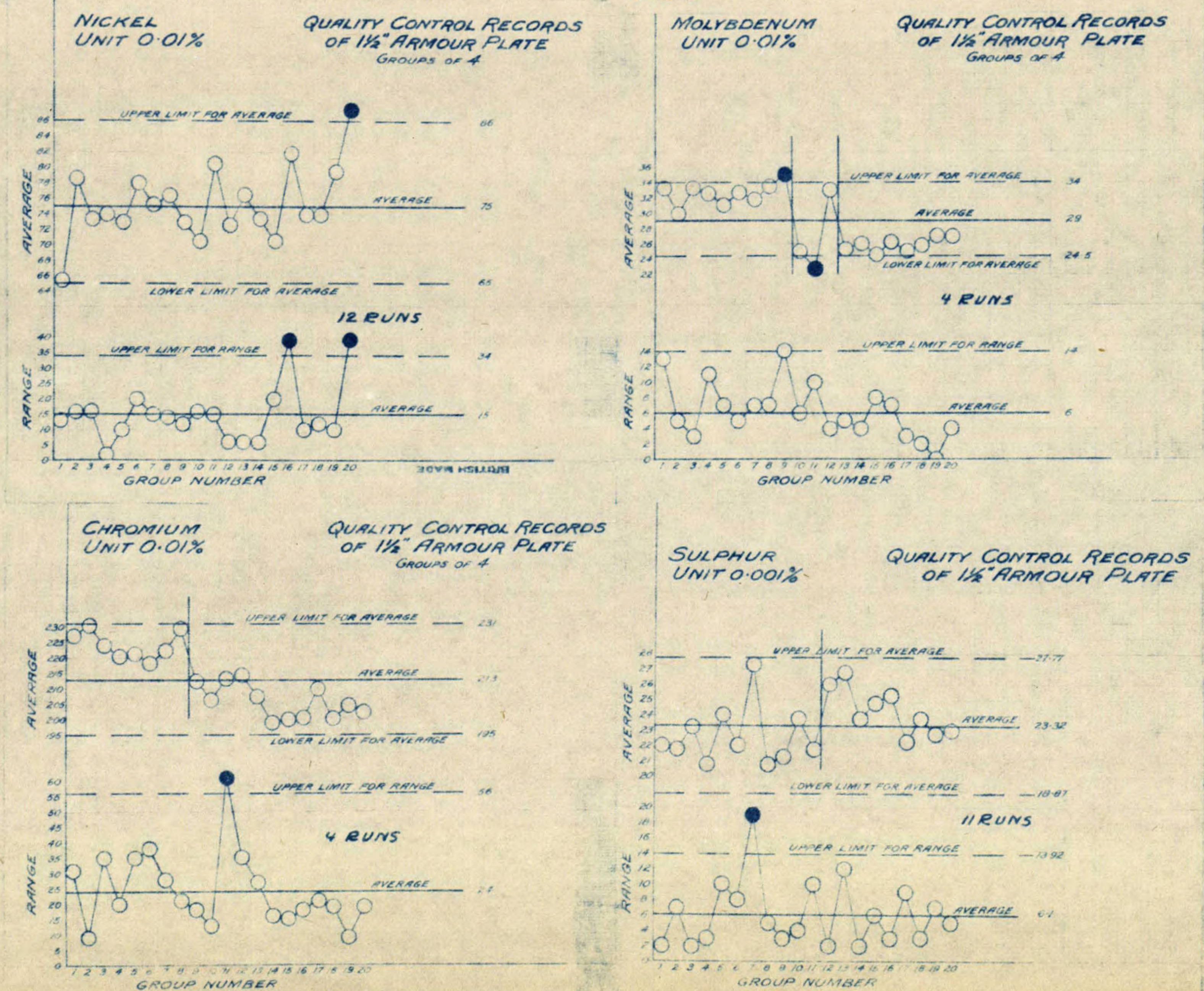
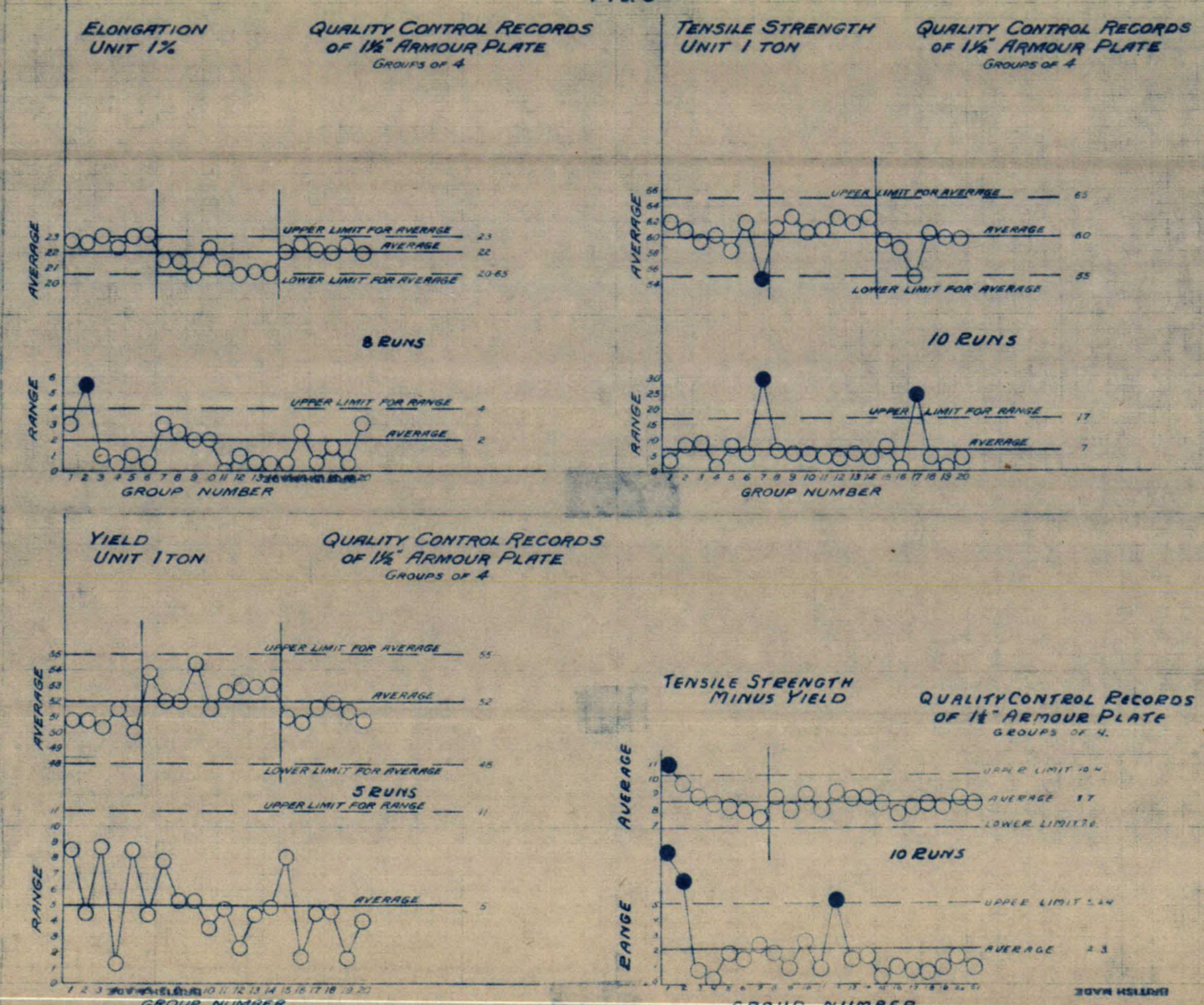
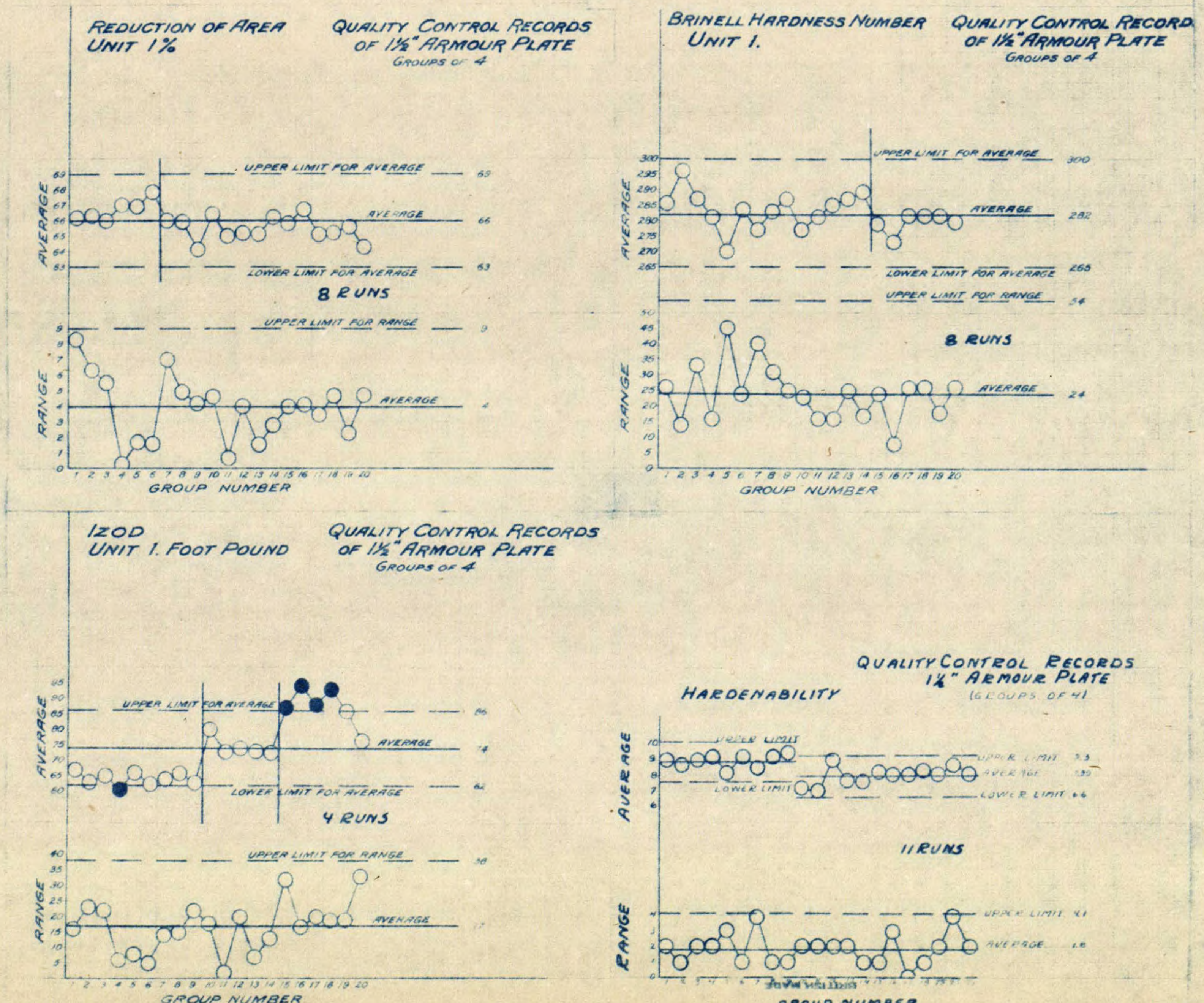

NICKEL
UNIT 0·01%
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
12 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
RANGE
GROUP NUMBER
MOLYBDENUM
UNIT 0·01%
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
4 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
RANGE
GROUP NUMBER
CHROMIUM
UNIT 0·01%
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
UPPER LIMIT FOR RANGE
4 RUNS
AVERAGE
RANGE
GROUP NUMBER
SULPHUR
UNIT 0·001%
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
11 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
RANGE
GROUP NUMBER

FIG. 3



ELONGATION
UNIT 1%
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
AVERAGE
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
23
22
20.65
8 RUNS
RANGE
UPPER LIMIT FOR RANGE
AVERAGE
4
2
GROUP NUMBER
TENSILE STRENGTH
UNIT 1 TON
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
AVERAGE
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
65
60
55
10 RUNS
RANGE
UPPER LIMIT FOR RANGE
AVERAGE
17
7
GROUP NUMBER
YIELD
UNIT 1 TON
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
AVERAGE
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
55
52
48
5 RUNS
UPPER LIMIT FOR RANGE
11
RANGE
AVERAGE
5
GROUP NUMBER
TENSILE STRENGTH
MINUS YIELD
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4.
AVERAGE
UPPER LIMIT
AVERAGE
LOWER LIMIT
10 RUNS
RANGE
UPPER LIMIT
AVERAGE
GROUP NUMBER

FIG. 4



REDUCTION OF AREA
UNIT 1%
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
8 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
RANGE
GROUP NUMBER
BRINELL HARDNESS NUMBER
UNIT 1.
QUALITY CONTROL RECORD
OF 1½" ARMOUR PLATE
GROUPS OF 4
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
UPPER LIMIT FOR RANGE
8 RUNS
AVERAGE
RANGE
GROUP NUMBER
IZOD
UNIT 1. FOOT POUND
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
4 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
RANGE
GROUP NUMBER
QUALITY CONTROL RECORDS
1½" ARMOUR PLATE
(GROUPS OF 4)
HARDENABILITY
UPPER LIMIT
LOWER LIMIT
AVERAGE
11 RUNS
RANGE
GROUP NUMBER

Conclusions:

The variation in chemical and physical properties which is characteristic of the manufacture of $1\frac{1}{2}$-in. armour plate has been shown graphically. This will serve as a guide for comparison with future operations.

During the period under investigation there were several changes made in the process of melting and heat treatment. The test values whose average shifted were:

Carbon	Elongation
Manganese	Tensile strength
Chromium	Yield strength
Molybdenum	Tensile minus yield
Hardenability	Impact strength

The drop in ballistic limit coincided with a drop in hardenability and tensile strength.

SECTION THREE. - Correlation Between Ballistic Limit and Metallurgical Properties of $1\frac{1}{2}$-in. Armour Plate.

Physical Properties:

In Report of Investigation No. 1537 (December 4th, 1943), entitled "A New Method of Determining the Projectile Penetration Resistance of Armour Plate," the correlation between physical tests and ballistic properties was shown. Optimum physical properties, so far as ballistic limit is concerned, are as follows:

Yield strength	-	52.8-57.1 tons/sq.in.
Impact	-	48-76 ft-lb.
Tensile strength	-	59.3-65.1 tons/sq.in.
Brinell hardness	-	281-289.

Chemical Properties:

The charts on Pages 12, 13 and 14 show the relationships between chemical and ballistic limit tests.

The information was first put in scatterplot form. Half of the ballistic limit values were above 1360 ft./sec.

The chemical test values were divided into three approximately equal groups. For example, phosphorus results were as follows:

Phosphorus range	Number of results above 1360 ft./sec.	Number of results below 1360 ft./sec.	Per cent of results above 1360 ft./sec.
0.014-0.020	14	11	56
0.021-0.024	21	14	60
0.025-0.035	7	15	32

The results which appeared to be significant according to the Chi Square test are (Appendix B, Chi Square explanation, pp. 38-41):

Element		Optimum Range
Manganese	-	0.50-0.64.
Silicon	-	0.15-0.28 and 0.33-0.35.
Phosphorus	-	0.014-0.024.
Sulphur	-	0.016-0.022.
Chromium	-	0.206-0.217.
Molybdenum	-	0.32-0.42.

(Continued on next page)

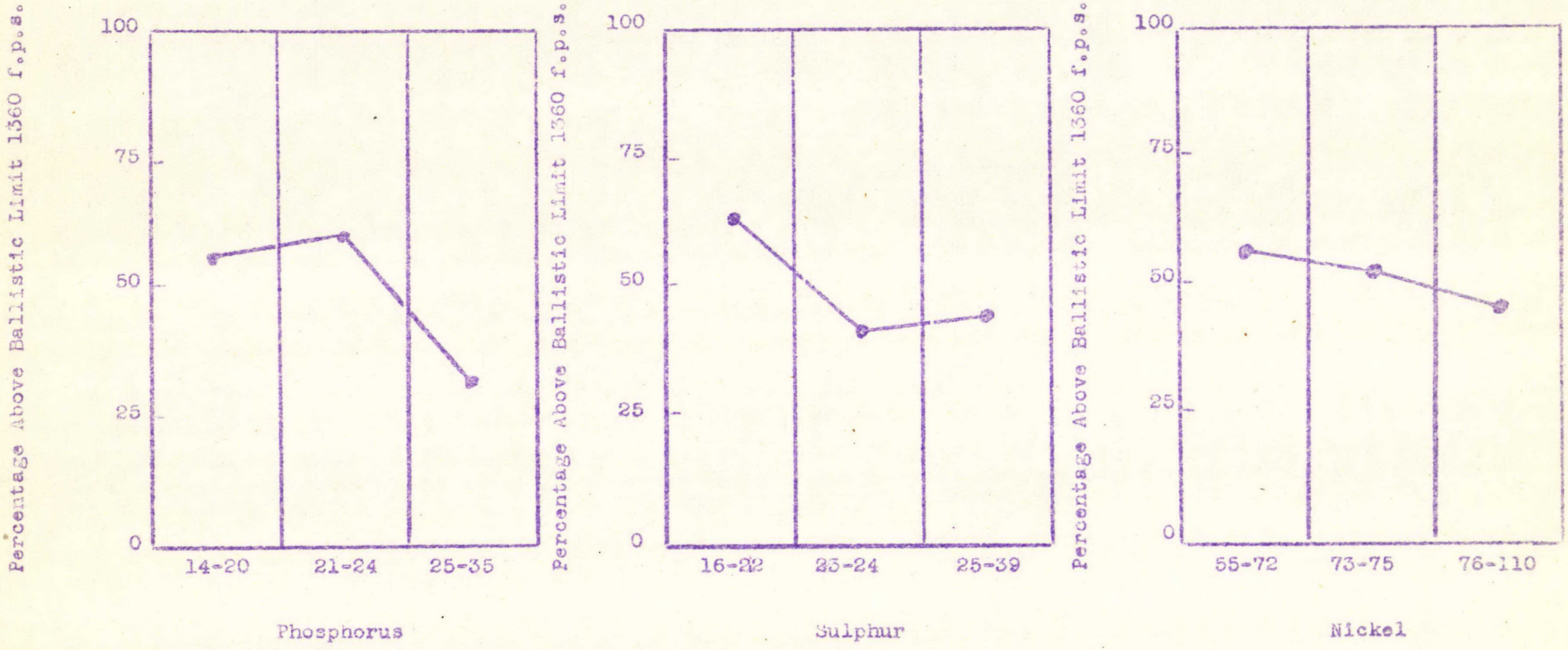
(Chemical Properties, cont'd) -

There is also an indication that hardenability should not be below 9 on the Grossman scale.

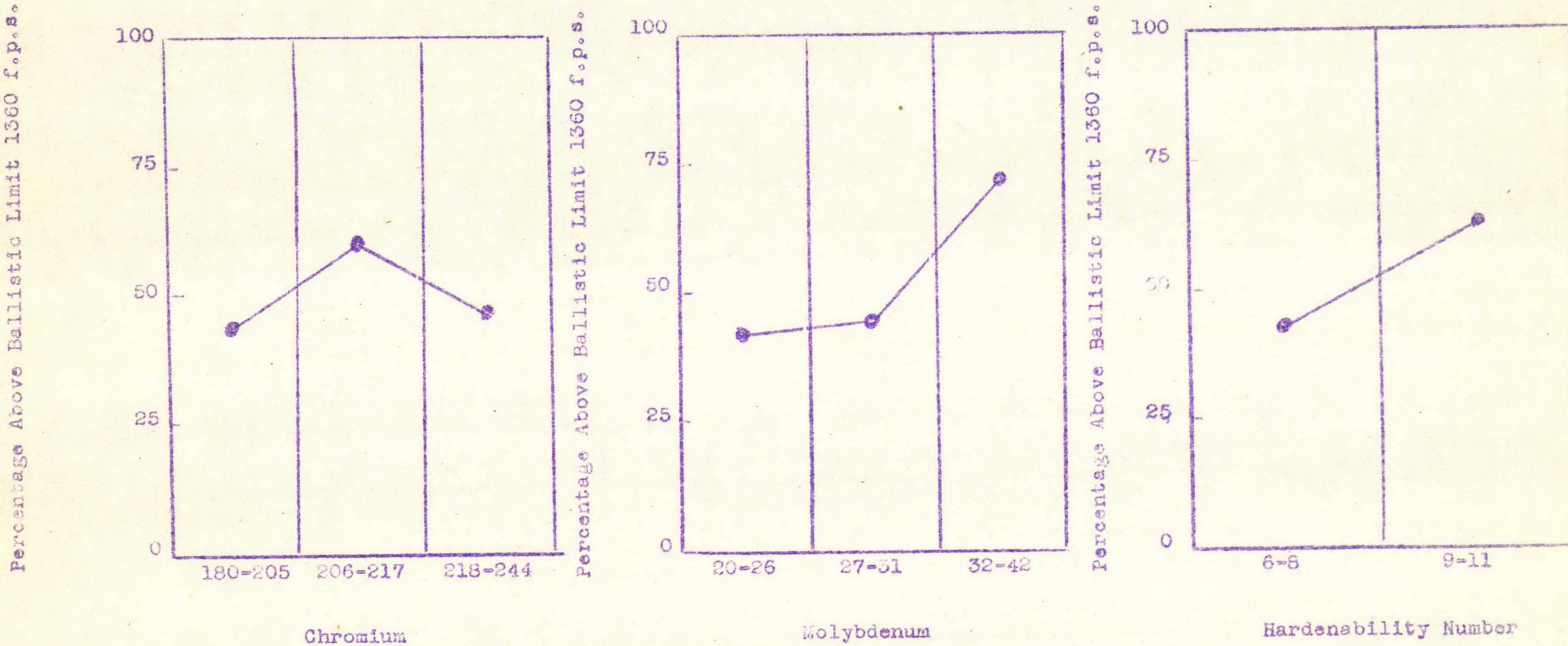
Since the process was changed several times during the period investigated, a correlation might occur because a run of high test values coincided with a change in the process. The process change may have been **the causative** agent, and the chemical test value merely a coincident phenomena.

It is readily apparent that variation in chemical analysis within the range examined is not a significant source of variation of ballistic properties. Physical tests are much more closely related to ballistic limits.

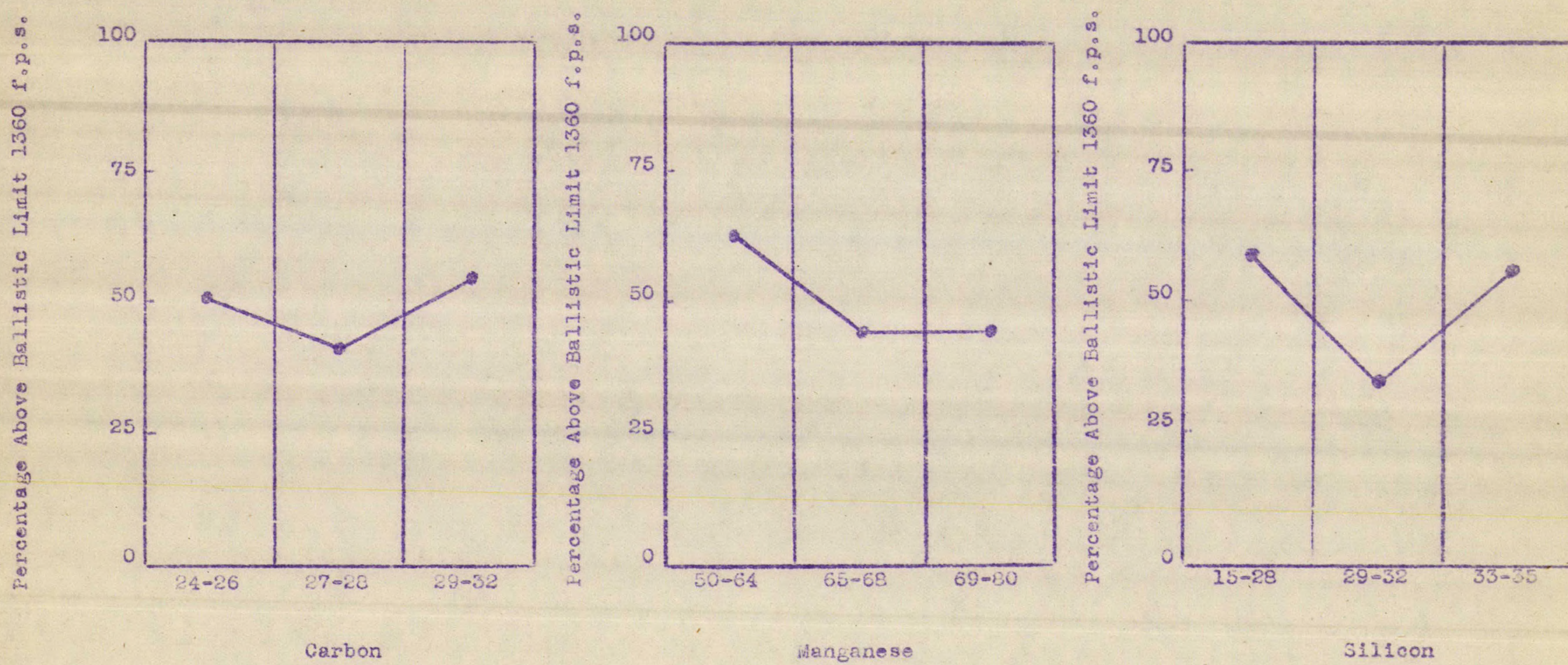
(Pages 12, 13 and 14 are)
(charts mentioned on Page 10.)



(Relationship between Chemical Properties and Ballistic Limit) -



(Relationship between Chemical Properties and Ballistic Limit, cont'd) -



(Relationship between Chemical Properties and Ballistic Limit, cont'd) -

Conclusions:

Optimum physical properties for $1\frac{1}{2}$-in. armour (so far as ballistic limit is concerned) have been given in Report of Investigation No. 1537. They are as follows:

Yield strength	-	52.8-57.1 tons/sq.in.
Tensile strength	-	48-76 ft-lb.
Impact	-	59.3-65.1 tons/sq.in.
Brinell hardness	-	281-289.

With respect to the chemical analysis of armour plate the following general conclusions, which are tentative and may be changed when more information becomes available, have been drawn from this and other work:

1. Sulphur and phosphorus usually correlate with ballistic limit because their variation is a reflection of variation in melting practice.

2. An optimum range for carbon content appears to be 0.28-0.32 per cent.

3. Over 2.50 per cent chromium is undesirable. Ballistic limit drops off above this value, due to the embrittling effect of undissolved carbides.

4. Under 0.25 per cent molybdenum, there is a possibility that armour may be temper brittle.

5. Above 0.65 per cent molybdenum, ballistic limit falls off, due to undissolved carbides.

6. Grossman hardenability is correlated to ballistic limit.

7. Manganese, silicon, nickel, chromium, and molybdenum do not usually correlate with ballistic limit. This is because any effect they exert on armour properties is through their effect on hardenability.

8. No evidence has been advanced to show that there is any superior combination of alloys for armour. The wide variety of analyses used by various armour makers testifies to this statement. Each manufacturer has arrived at an analysis with which he can successfully make armour. The analysis suits the equipment available and the methods used.

SECTION FOUR. - Through-Plate Tensile Tests on 1½-inch Armour Plate.

Origin:

Appendix C, on Page 42, shows the plate numbers from R-3 to R-45 arranged in groups of 2. From each of these plates, three test pieces were taken so that their length was the thickness of the plate. The cross-section area of the test specimens was 0.02 square inch. A ½-in. gauge length was used for the elongation and reduction of area measurements.

The physical test results obtained were plotted in groups of six. The groups comprised the plates shown in Appendix "C". The nature of the "N" value test is described in Appendix "D", Page 43.

Comments:

Groups 2 to 8 inclusive have a below-average run in ballistic limit and also in reduction of area. It has been pointed out by other observers that through-plate reduction of area is correlated to ballistic limit.

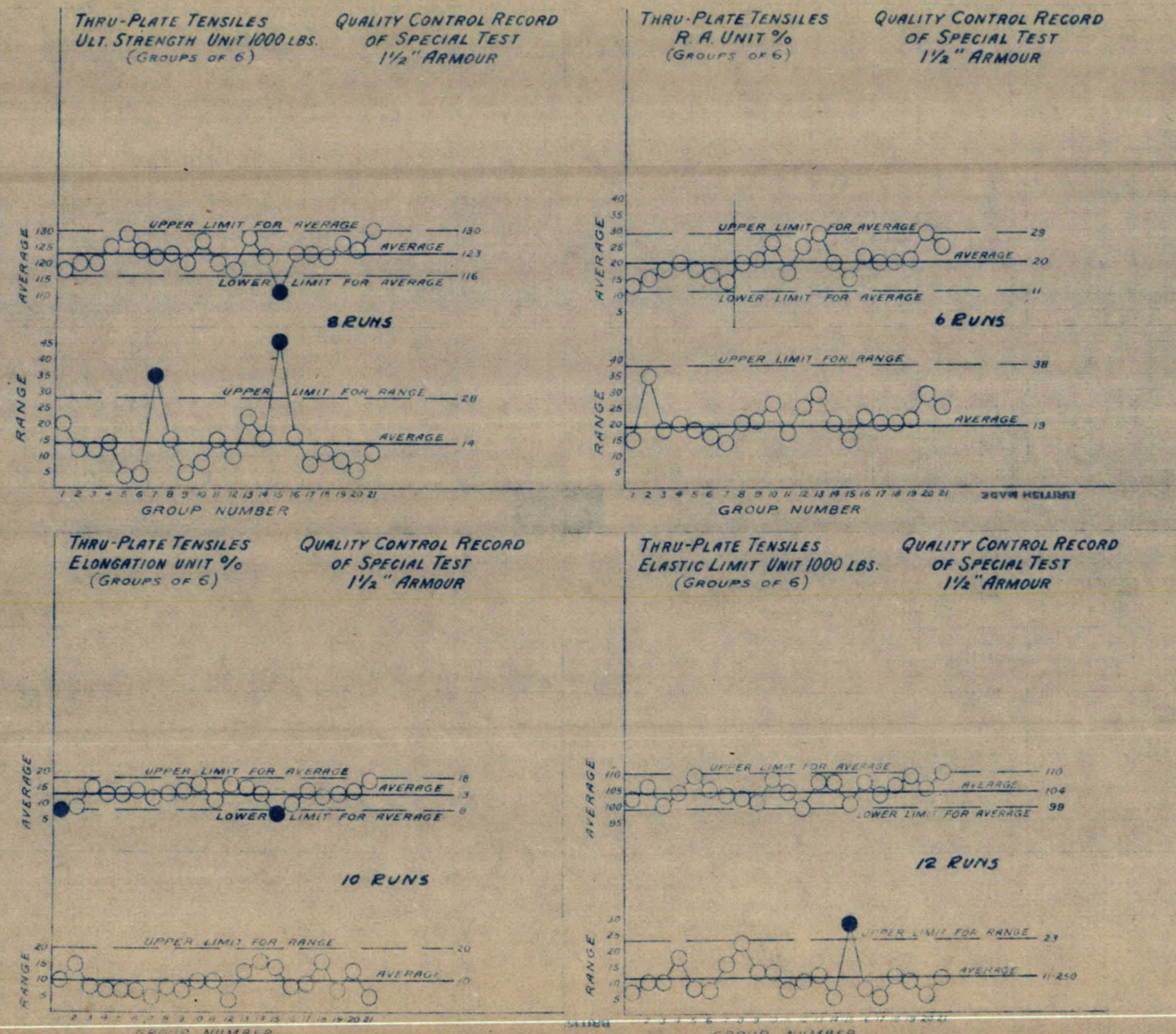
The properties which are not controlled to a constant level of quality are:

Ballistic limit,
Reduction of area,
Back damage factor,
Inclusion rating.

Limits within which other properties of the armour normally fall are indicated on the following charts, Figures 5, 6, 7 and 8.

(Figures 5 to 8, charts,)
(follow on Pages 17 to 20.)

FIG. 5


THRU-PLATE TENSILES
ULT. STRENGTH UNIT 1000 LBS.
(GROUPS OF 6)
QUALITY CONTROL RECORD
OF SPECIAL TEST
1½" ARMOUR
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
8 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
GROUP NUMBER
THRU-PLATE TENSILES
R. A. UNIT %
(GROUPS OF 6)
QUALITY CONTROL RECORD
OF SPECIAL TEST
1½" ARMOUR
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
6 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
GROUP NUMBER
THRU-PLATE TENSILES
ELONGATION UNIT %
(GROUPS OF 6)
QUALITY CONTROL RECORD
OF SPECIAL TEST
1½" ARMOUR
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
10 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
GROUP NUMBER
THRU-PLATE TENSILES
ELASTIC LIMIT UNIT 1000 LBS.
(GROUPS OF 6)
QUALITY CONTROL RECORD
OF SPECIAL TEST
1½" ARMOUR
UPPER LIMIT FOR AVERAGE
AVERAGE
LOWER LIMIT FOR AVERAGE
12 RUNS
UPPER LIMIT FOR RANGE
AVERAGE
GROUP NUMBER

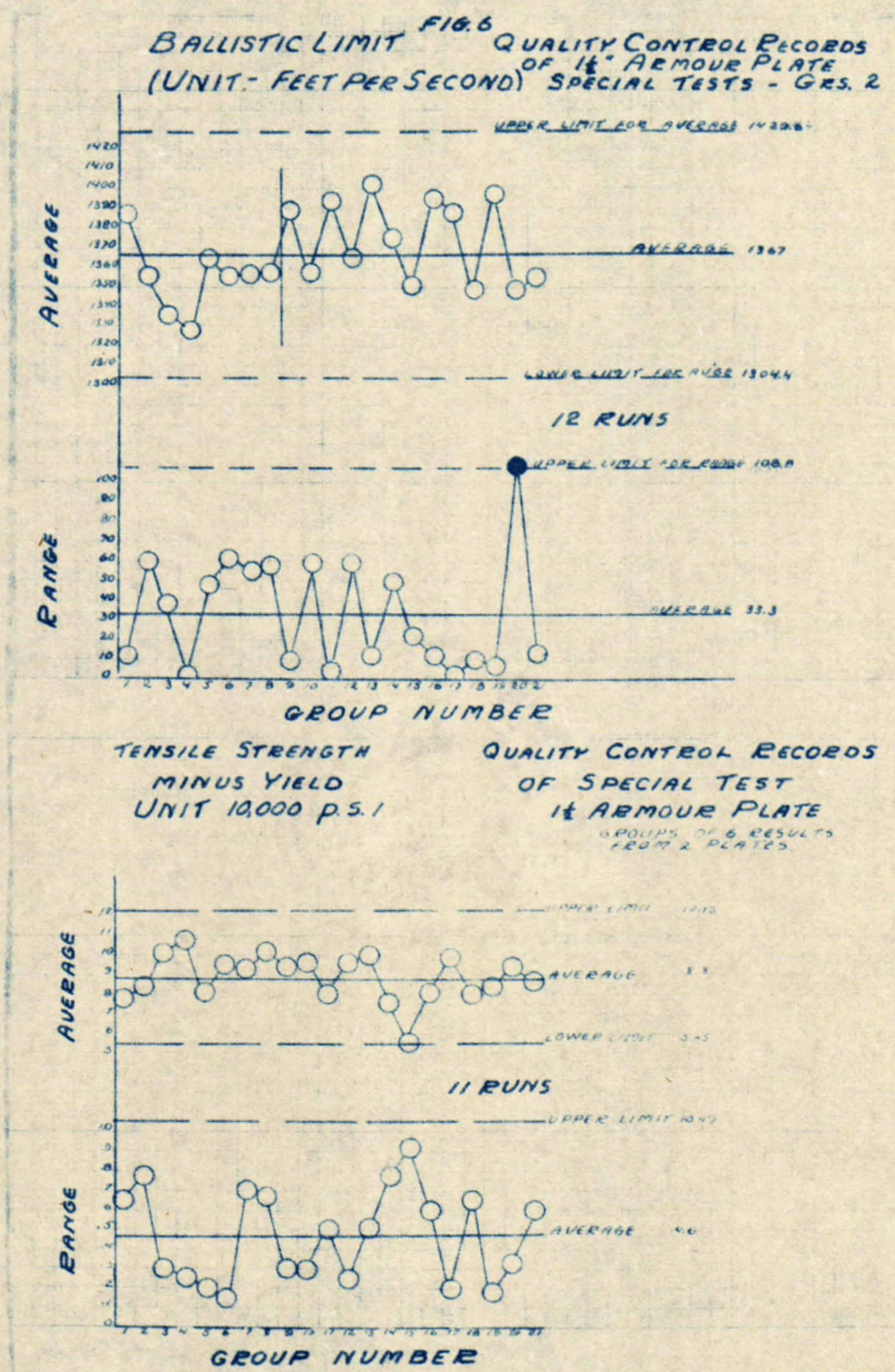


FIG. 6
BALLISTIC LIMIT
(UNIT - FEET PER SECOND)
QUALITY CONTROL RECORDS OF 1¼" ARMOUR PLATE
SPECIAL TESTS - GRS. 2
UPPER LIMIT FOR AVERAGE 1429.6
AVERAGE 1367
LOWER LIMIT FOR AVGE 1304.4
12 RUNS
UPPER LIMIT FOR RANGE 108.8
AVERAGE 33.3
AVERAGE
RANGE
GROUP NUMBER
TENSILE STRENGTH MINUS YIELD
UNIT 10,000 P.S.I
QUALITY CONTROL RECORDS OF SPECIAL TEST 1¼ ARMOUR PLATE
GROUPS OF 6 RESULTS FROM 2 PLATES
AVERAGE
LOWER LIMIT
11 RUNS
UPPER LIMIT
AVERAGE
RANGE
GROUP NUMBER

FIG. 7

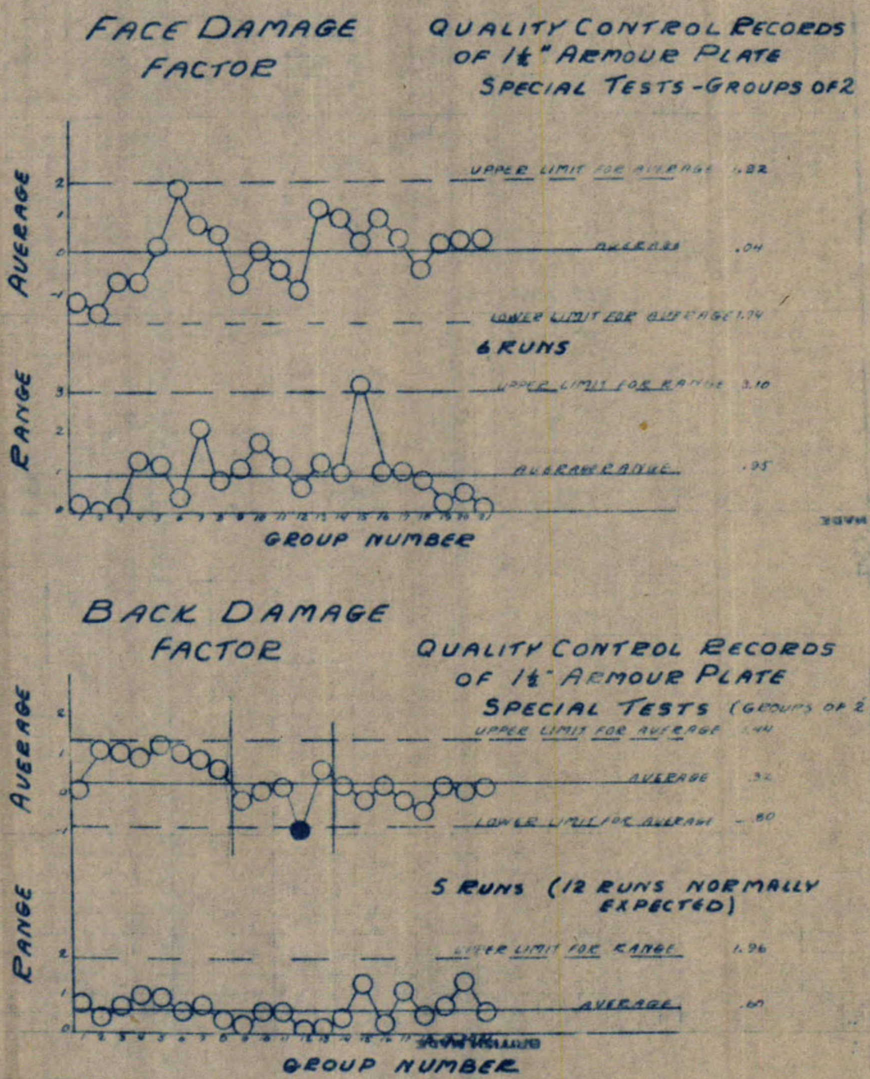
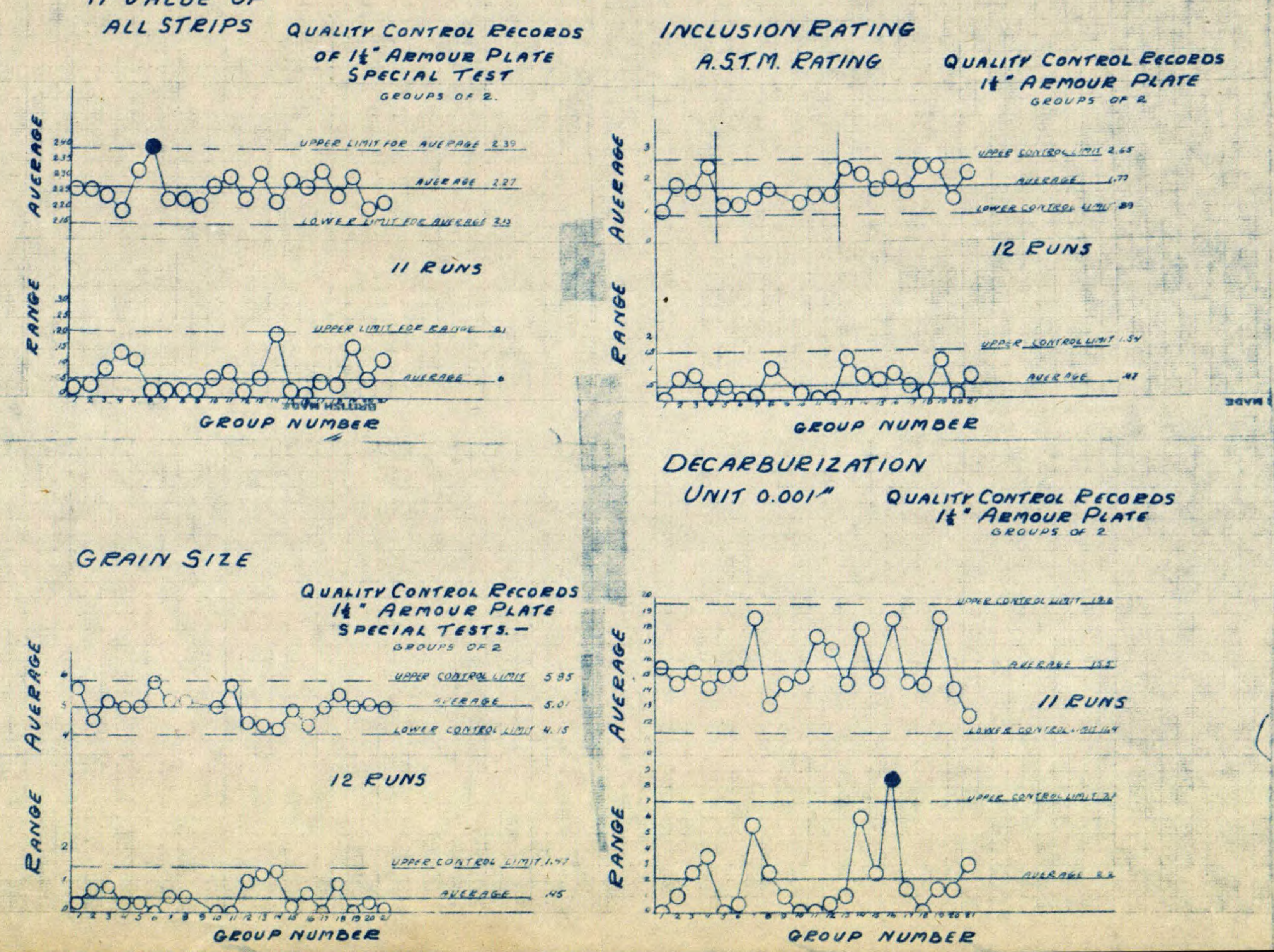

FACE DAMAGE FACTOR
QUALITY CONTROL RECORDS OF 1½" ARMOUR PLATE
SPECIAL TESTS - GROUPS OF 2
AVERAGE
UPPER LIMIT FOR AVERAGE 1.82
AVERAGE .04
6 RUNS
RANGE
UPPER LIMIT FOR RANGE 3.10
AVERAGE RANGE .95
GROUP NUMBER
BACK DAMAGE FACTOR
QUALITY CONTROL RECORDS OF 1½" ARMOUR PLATE
SPECIAL TESTS (GROUPS OF 2
AVERAGE
UPPER LIMIT FOR AVERAGE 1.44
AVERAGE .32
LOWER LIMIT FOR AVERAGE -.80
5 RUNS (12 RUNS NORMALLY EXPECTED)
RANGE
UPPER LIMIT FOR RANGE 1.96
AVERAGE .60
GROUP NUMBER

FIG. 8


"n" VALUE OF ALL STRIPS
QUALITY CONTROL RECORDS OF 1¼" ARMOUR PLATE SPECIAL TEST
GROUPS OF 2.
AVERAGE
UPPER LIMIT FOR AVERAGE 2.39
AVERAGE 2.27
LOWER LIMIT FOR AVERAGE 2.15
11 RUNS
RANGE
UPPER LIMIT FOR RANGE .21
AVERAGE
GROUP NUMBER
INCLUSION RATING
A.S.T.M. RATING
QUALITY CONTROL RECORDS 1¼" ARMOUR PLATE
GROUPS OF 2
AVERAGE
UPPER CONTROL LIMIT 2.65
AVERAGE 1.77
LOWER CONTROL LIMIT .89
12 RUNS
RANGE
UPPER CONTROL LIMIT 1.54
AVERAGE .47
GROUP NUMBER
GRAIN SIZE
QUALITY CONTROL RECORDS 1¼" ARMOUR PLATE SPECIAL TESTS.—
GROUPS OF 2
AVERAGE
UPPER CONTROL LIMIT 5.85
AVERAGE 5.01
LOWER CONTROL LIMIT 4.15
12 RUNS
RANGE
UPPER CONTROL LIMIT 1.47
AVERAGE .45
GROUP NUMBER
DECARBURIZATION
UNIT 0.001"
QUALITY CONTROL RECORDS 1¼" ARMOUR PLATE
GROUPS OF 2
AVERAGE
AVERAGE 15.5
11 RUNS
RANGE
GROUP NUMBER

SECTION FIVE. - Relationship of Decarburization to Ballistic Limit.

Method:

Specimens were examined microscopically, at 100 diameters, but the decarburization merged into the central structure of the steel so gradually that it was difficult to obtain a definite line of demarcation. The photomicrograph, Figure 9, shows the difficulty of microscopic measurement.

It was decided, therefore, to measure decarburization by taking hardness readings from the outer edge towards the centre. These results were plotted and the point at which the curve flattened out was taken as depth of decarburization. Figure 10 indicates how the hardness results were plotted.

Decarburization Correlated to Back Crackage:

Plates on which no cracking occurs when the bulge on the back is ½-in. high are listed as "good". Plates on which cracks appear when the bulge on the back is ½-in. are listed as "bad". The depth of decarburization of a set of "good" and of "bad" plates is given in Table I.

TABLE I.

Depth of decarburization of "good" plates	Depth of decarburization of "bad" plates
16.5 x 0.1 mm.	15.5 x 0.1 mm.
15.0 x " "	14.0 x " "
15.0 x " "	15.0 x " "
21.5 x " "	14.0 x " "
16.0 x " "	12.5 x " "
14.5 x " "	16.0 x " "
15.0 x " "	12.0 x " "
17.5 x " "	16.0 x " "
16.5 x " "	15.0 x " "
13.5 x " "	13.5 x " "
14.5 x " "	14.0 x " "
13.5 x " "	14.5 x " "
14.0 x " "	11.0 x " "

The analysis of variance technique (see Appendix E, on Page 44) shows that there is a significant difference in the

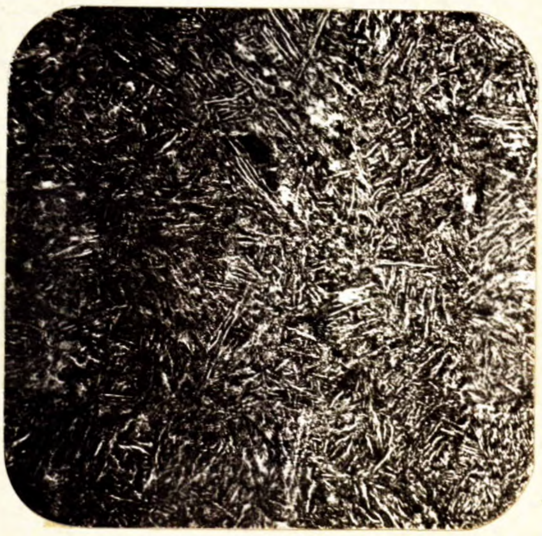
(Decarburization Correlated to Back Crackage, cont'd) -

decarburization of the "good" and the "bad" plates. Therefore, it may be stated that deeper decarburization is a characteristic of the better armour plates.

Decarburization Correlated to Ballistic Limit:

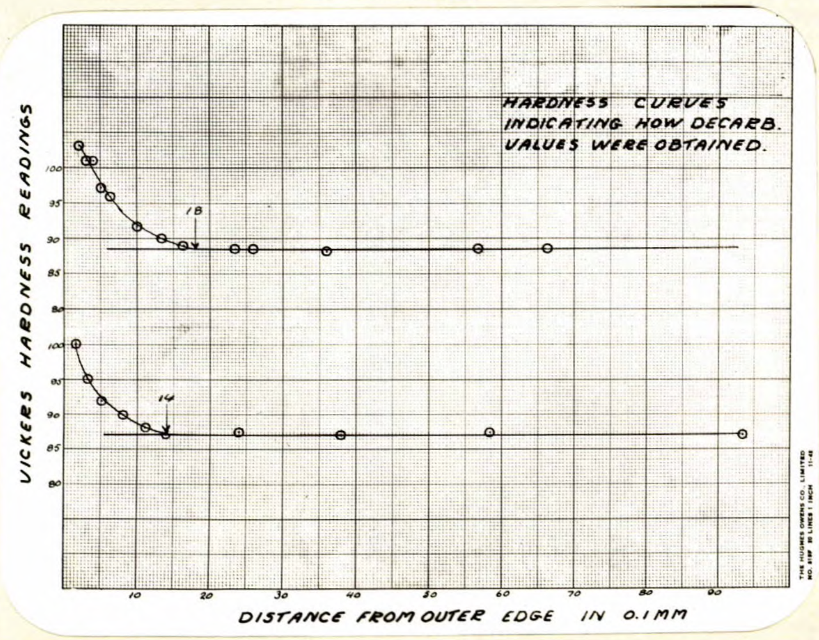
Figure 11 represents the scatterplot showing decarburization and ballistic limit values. It is evident from the analyses of this data that higher ballistic limits are characteristic on the more deeply decarburized plates.

Figure 9.



X100, nital etch.
Note difficulty in determining line of demarcation of decarburization zone.

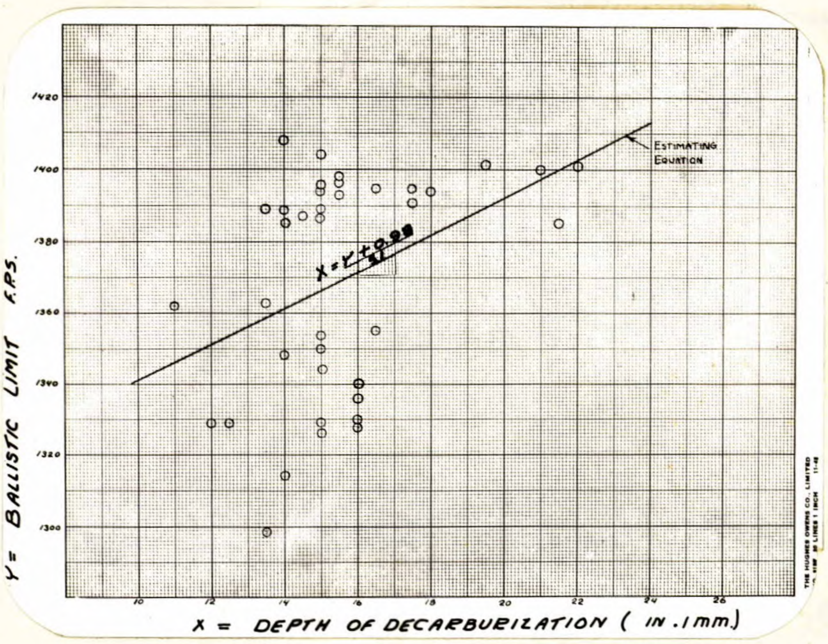
Figure 10.



The point at which curved portion meets the base line gives a measure of depth of decarburization.

(Decarburization Correlated to Ballistic Limit, cont'd) -

Figure 11.



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Conclusions:

Since decarburization is closely associated with two desirable characteristics of armour plate (back crackage and ballistic limit), investigations should be made to find out how some use can be made of this information.

The advantage of decarburization has been commercially exploited by the National Armour Co., Indiana. Armour made and decarburized by the Follansbee Steel Co. is heat-treated by the above concern. Higher ballistic limits are obtained than from any other armour source. The reasons for the superiority of decarburized armour may be:

(a) The longer the armour is in the furnace the greater is the depth of decarburization. Furnace time may be the deciding factor.

(b) The higher temperature of the furnace, the better the armour. The deeper decarburization is merely coincidental.

(c) The soft, ductile skin on the back of the armour plate may be the controlling factor.

(Continued on next page)

(Conclusions, cont'd) -

It is generally assumed that a soft surface on the front of armour plate will assist the projectile.

This information on decarburization should be further clarified by experimental work.

SECTION SIX. - Relationship Between Inclusions and Ballistic Qualities.

Method:

Specimens from forty-five (45) consecutive heats were hardened, polished, and then examined at 100 diameters. The rating system used was that of the American Society for Testing Materials. It was found that samples could be placed in three groups, viz.,

Group 1 - ASTM rating of 1.0 - 1.4

Group 2 - ASTM rating of 1.5 - 1.9.

Group 3 - ASTM rating of 2.0 and up.

By taking ten readings on each specimen an average representative figure was derived for each sample.

Inclusions as Correlated to Back Crackage:

As previously mentioned, armour plates were divided into "good" and "bad", "good" plates being the ones on which ½-in. bulges appeared on the back without any cracks. A comparison of inclusion ratings with "good" and "bad" plates is given in Table II.

TABLE II.

Inclusion Range	1 - 1.4	1.5 - 1.9	2.0 - up
Ballistic Properties	8 Good. 4 Bad.	3 Good. 2 Bad.	1 Good. 9 Bad.

These results significantly indicate that the cleanliness of the steel is closely related to the formation of cracks on the back of the plate.

Inclusions As Related to Ballistics:

TABLE III.

Inclusion range	1 - 1.4	1.5 - 1.9	2.0 - up
Average ballistic limit, in ft./sec.	1369	1368	1362

These results only indicate that possibly a larger number of tests would show a definite relationship between ballistic limit and number of inclusions.

Correlation to Physical Properties:

It was not possible to find any significant relationship between inclusions and through-plate tensile, elongation, or reduction of area. This is evidence of the cleanliness of the steel, for it has been previously discovered that inclusions have a marked effect in varying through-plate tensile tests.

Type of Inclusions:

Figures 12, 13 and 14 are photomicrographs showing the appearance of the inclusions, at 100 diameters.

A closer examination of the inclusions, at 2000 diameters, showed that grey elongated inclusions were the type most prominent in all specimens. (See Figure 14).

With reference to the scheme for etching indentification tests of inclusions, as shown in Metals Handbook, a means for a more accurate classification was determined. The inclusions were found to darken under a 10 per cent nital etch and to be removed by a 5 minute 10 per cent chromic acid etch. This gave sufficient evidence to prove that sulphides and oxides of manganese and iron were the typical inclusions.

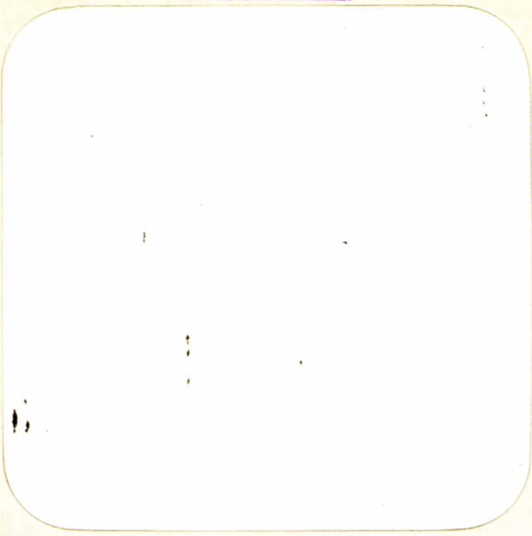
Conclusion and Recommendation:

The appearance of cracks has therefore been shown to correlate with the volume of inclusions.

Due to the evident relationship of inclusions to armour quality, it would be well to adopt Inclusion Rating as a standard metallurgical test. This would offer a guide to permit control over the varying conditions for inclusion formation during the steel-making process.

(Figures 12, 13 and 14)
(follow, on Page 28.)

Figure 12.



X100.

A SAMPLE OF "CLEAN" STEEL.

Average ASTM rating, 1.4.

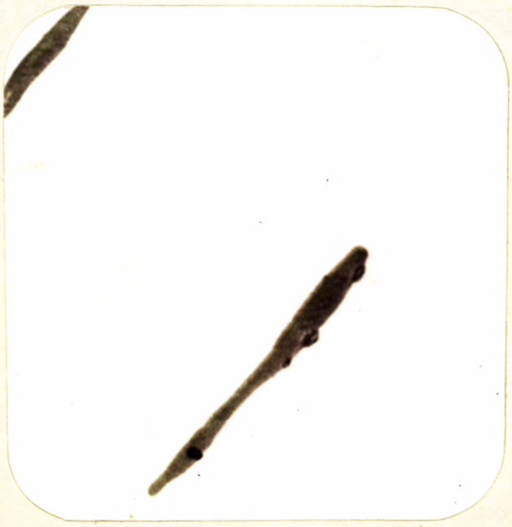
Figure 13.

X100.

A SAMPLE OF "DIRTY" STEEL.

Average ASTM rating, 2.5.

Figure 14.



X2000.

SAMPLE OF TYPICAL SULPHIDE INCLUSION.

SECTION SEVEN.- Relationship Between Grain Size and Microstructure and Ballistic Properties.

Purpose:

The purpose of this section is to investigate the correlation of grain size and microstructure with ballistic properties of 1½-in. armour plate made by Dominion Foundries and Steel Limited.

Preparation for Micro-analysis of Structure:

The specimens were given a 1-minute picral etch and examined at 1,000 diameters for structure. This appeared as a typical tempered martensite. However, there were sufficient differences in the appearance of the various samples that two classifications were adopted.

The first group (Figure 15) shows a banded structure probably caused by segregation of the alloying elements. The second group (Figure 16), although not perfectly homogenized, does not show the decided segregated areas and banding.

Microstructure as Correlated to Back Crackage:

The results of firing-range tests on armour plate give a measure of the height of bulge formed on the back of the plate due to penetration of the round.

Plates on which no cracking occurs on the ½-in. bulge surface are, for the purposes of this report, listed as "GOOD". Plates on which cracks appear on the ½-in. bulge surface are called "BAD".

Upon listing the two types of structures under this grouping, we find:

Type of Structure		Homogeneous	Segregated
Good Plate	-	10	4
Bad Plate	-	8	6

These figures do not show conclusively that one

(Microstructure as Correlated to Back Crackage, cont'd) -

type of structure is better than the other, but merely give an indication that upon more extensive examination a homogeneous structure <u>might</u> be preferable.

<u>Structure as Correlated to Ballistic Limit:</u>

Type of structure		Average ballistic limit
Homogeneous	-	1366.0 ft./sec.
Segregated	-	1371.0 "

Statistical methods demonstrate that the above difference is <u>not significant</u>.

<u>Structure as Correlated to Physical Properties:</u>

There was no relationship found between type of structure and through-plate tensile, elongation, or reduction of area; also, there was no correlation with face or back damage.

<u>Preparation for Grain-Size Measurement:</u>

Specimens were heat treated under the McQuaid-Ehn requirements for grain size examination. The most successful etch was with an alkaline potassium ferricyanide which darkens the cementite precipitated at the grain boundary. Classification was best made by stating as "mixed" or "uniform" grain size (see Figures 17 and 18). With reference to A.S.T.M. standards, a representative number was given each sample. (The number 5 was most prominent).

<u>Grain Size as Correlated to Back Crackage:</u>

The means of classifying the plates as "Good" or "Bad" has been described in the discussion of this feature with

(Grain Size as Correlated to Back Crackage, cont'd) -

regard to microstructure.

Type of Grain		Mixed	Uniform
Good	-	3	10
Bad	-	5	8

Here again we have only a slight indication that the uniform grain is superior.

Size of Grain		3.5-4.7	4.8-5.2	5.3-6.0
Good	-	2	10	2
Bad	-	4	8	4

The results although showing preference of the second column are hardly significant, especially when we consider the greater number of specimens available in that size of grain. Thus, it is not possible to state that one grain size is better than another.

Grain Size as Correlated to Ballistic Limit:

Type of Grain	-	Mixed	Uniform
AVERAGE BALLISTIC LIMIT	-	1370 ft./sec.	1366 ft./sec.

Size of Grain	-	3.5-4.7	4.8-5.2	5.3-6.0
AVERAGE BALLISTIC LIMIT	-	1371 ft./sec.	1361 ft./sec.	1368 ft./sec.

From the above results it is assumed that grain size is so closely controlled that it has little or no effect upon ballistic qualities.

Discussion of Results:

The similar correlation of grain size and microstructure to ballistic properties indicates a strong relationship present.

(Continued on next page)

(Discussion of Results, cont'd) -

Type of Structure	-	Homogeneous	: Segregated
MIXED GRAIN SIZE	-	4	9
UNIFORM GRAIN SIZE	-	18	5

This is suggestive that the segregated portions containing higher alloy would cause a sluggish grain growth, whereas the alloy-rare portions would permit free grain growth. Thus we have a means of interpreting the relationship of mixed grain size and segregated structure.

Conclusions:

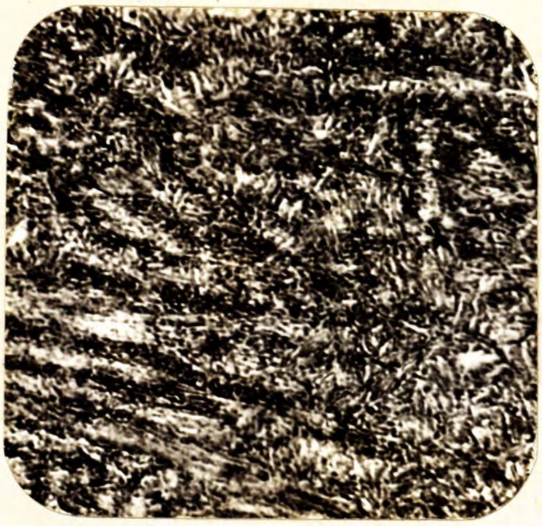
From the results presented it would appear that taking special precautions in order to obtain homogeneity is not necessary for armour plate steels. Evidence has shown that with homogeneous and segregated structures neither one is correlated in any way with ballistic properties.

Mr. F. Sherman Jr., of the Dominion Foundries and Steel Limited, suggested that the segregated structure may have been due to the fact that the sample was taken from the centre of the original plate. The homogeneous structure may have occurred in samples taken from the edge of the plate.

The term homogeneity is used in the micro-chemical sense. It refers to banded structures caused by uneven alloy distribution.

(Figures 15 to 18)
(follow, on Page 33.)

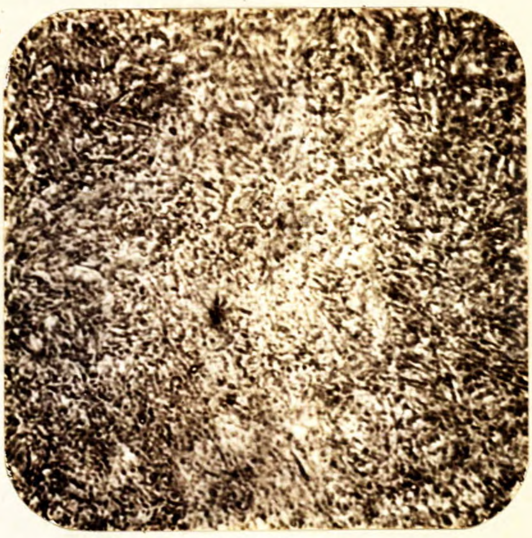
Figure 15.



X1000, picral etch.

NOTE BANDED STRUCTURE.

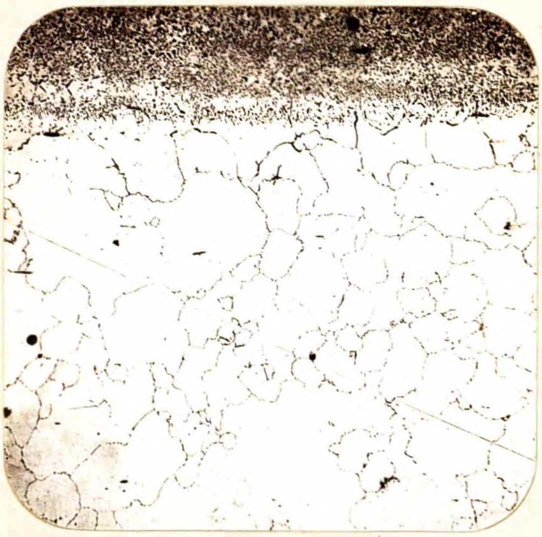
Figure 16.



X1000, picral etch.

HOMOGENEOUS TEMPERED MARTENSITE.

Figure 17.



X100, alkaline $K_3Fe(CN)_6$ etch.

MIXED GRAIN SIZE, A.S.T.M. 2 to 6.

Figure 18.

X100, alkaline $K_3Fe(CN)_6$ etch.

UNIFORM GRAIN SIZE, A.S.T.M. NO. 5.

SECTION EIGHT. - Further Process Research on Armour.

The quality control charts included in this report have indicated the variation in properties which is characteristic of the process. The variation in yield strength normally expected is such that within four heats taken consecutively a difference as great as 11 tons may occur.

Since yield strength correlates with ballistic limit, the variation in yield strength undoubtedly causes a variation in ballistic limit.

The variation in primary factors such as yield, inclusion content, sulphur, etc., is therefore responsible for the variation in ballistic properties. These primary factors are, however, under the influence of secondary process variables.

A program of research on the armour-plate process has only commenced when primary factors (metallurgical properties) have been correlated to ballistic properties. Further investigation is needed to find out the effect of operating variables upon metallurgical properties, steel mill scrap, and ballistic properties.

F. Sherman, Jr., of Dominion Foundries and Steel Limited, Hamilton, Ontario, has prepared a very interesting report showing the relationship of melting process variables upon ballistic limit. As this work progresses more and more useful information will be brought to light.

SECTION NINE. - SUMMARY OF CONCLUSIONS FROM ALL SECTIONS.

1. In making firing-range tests on armour plate, we attempt to determine the two essential characteristics of the plate, i.e.,

(a) its resistance to penetration, and

(b) its resistance to shock.

It has been shown, in Report of Investigation No. 1537, that only two shots are necessary to complete the required tests. The first should be at low velocity (1250 to 1335 ft./sec.), in order that it will not completely penetrate the plate. By measuring the depth of penetration we can refer this figure to the face damage chart (Figure 3 of Report of Investigation No. 1537) and determine the quality of the plate. This method would replace the taking of several bracketing shots to obtain an approximate ballistic limit.

The second shot should be fired at a higher velocity (1800 ft./sec.), sufficient to ensure penetration of the round. An examination of the exit hole on the back face will indicate the plate's ability to absorb shock.

2. From examination of the quality control charts submitted in this report, it is evident that several changes were made in the metallurgical processing of this steel during the test period.

3. The drop in ballistic limit coincides with the reduction of hardenability.

4. Yield, Tensile, Impact, and Brinell Hardness are all definitely related to ballistic limit.
Therefore, a closer control over heat treatment would probably reduce the variation in ballistic properties.

5. The through-plate physical tests had little relation to the ballistic limit of the plate, with the

(Summary of Conclusions, cont'd) -

exception of reduction of area.

6. All physical properties are closely related to the face damage factor.

7. The chemical analyses show a fairly close relation to ballistic properties.

8. A greater depth of decarburization reduces the tendency toward back crackage.

9. The number of inclusions correlates to back crackage. The cleaner steel is superior ballistically.

10. Grain size and microstructure, within the present operating limits, have no correlation with ballistic properties.

Since metallurgical tests are correlated with armour quality, it is probable that process variables are also related. It is understood that process variables are being studied with a view to obtaining more uniform and higher-quality plate.

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APPENDIX SECTION

Appendix A. - Grouping List (Groups of 4).

Appendix B. - Test for Significant Correlation by the "Chi-Square" Method.

Appendix C. - Grouping List (Groups of 2).

Appendix D. - "n" Value.

Appendix E. - Analysis of Variance Technique Applied to Depth of Decarburization.

APPENDIX A. - GROUPING LIST (Groups of 4).

Group No.	Plate No.	Group No.	Plate No.
1.	R1 R2 R3 R4	12.	R45 R46 R47 R48
2.	R5 R6 R7 R8	13.	R49 R50 R51 R52
3.	R9 R10 R11 R12	14.	R53 R54 R55 R56
4.	R13 R14 R15 R16	15.	R57 R58 R59 R60
5.	R17 R18 R19 R20	16.	R61 R62 R63 R64
6.	R21 R22 R23 R24	17.	R65 R66 R67 R68
7.	R25 R26 R27 R28	18.	R69 R70 R71 R72
8.	R29 R30 R31 R32	19.	R73 R74 R75 R76
9.	R33 R34 R35 R36	20.	R77 R78 R79 R80
10.	R37 R38 R39 R40	21.	R81 R82 R83
11.	R41 R42 R43 R44		

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APPENDIX B. - TEST FOR SIGNIFICANT CORRELATION BY "CHI-SQUARE" METHOD.

The chart shown on Page 40 has been designed to solve the problem of whether or not a significant correlation is present in a scatterplot of data.

Note, on Page 41, a typical scatterplot. The variables are: Face Damage Factor and Yield Strength. The question is, "Is there any connection between Face Damage and Yield Strength?"

The method used is as follows:

1. Divide the dots into equal halves by a horizontal line.

2. Divide the dots into equal halves by a vertical line.

3. Count the dots in each quadrant.

4. In upper left quadrant there are 13 dots. In lower left quadrant there are 29 dots.

   Let a = 13,
   b = 29.

   Therefore,

   a+b = 42
   a-b = 16.

   On the Chi-Square chart, the intersection of a+b = 42 and a-b = 16 gives the probability that the observed correlation is significant. The odds are that a real correlation exists about 99 out of 100.

5. It is possible to state that low yield strength correlates with low face damage.

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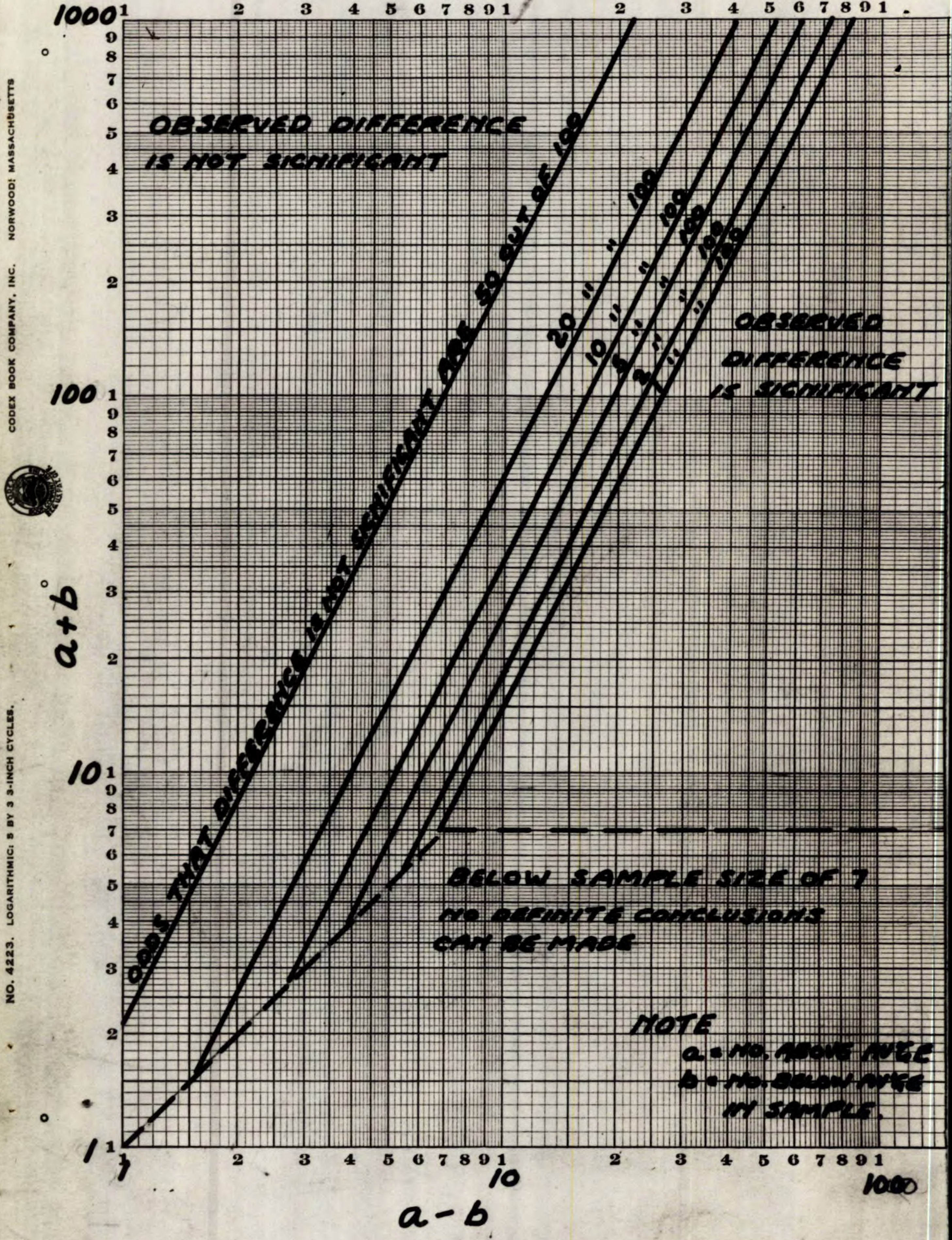
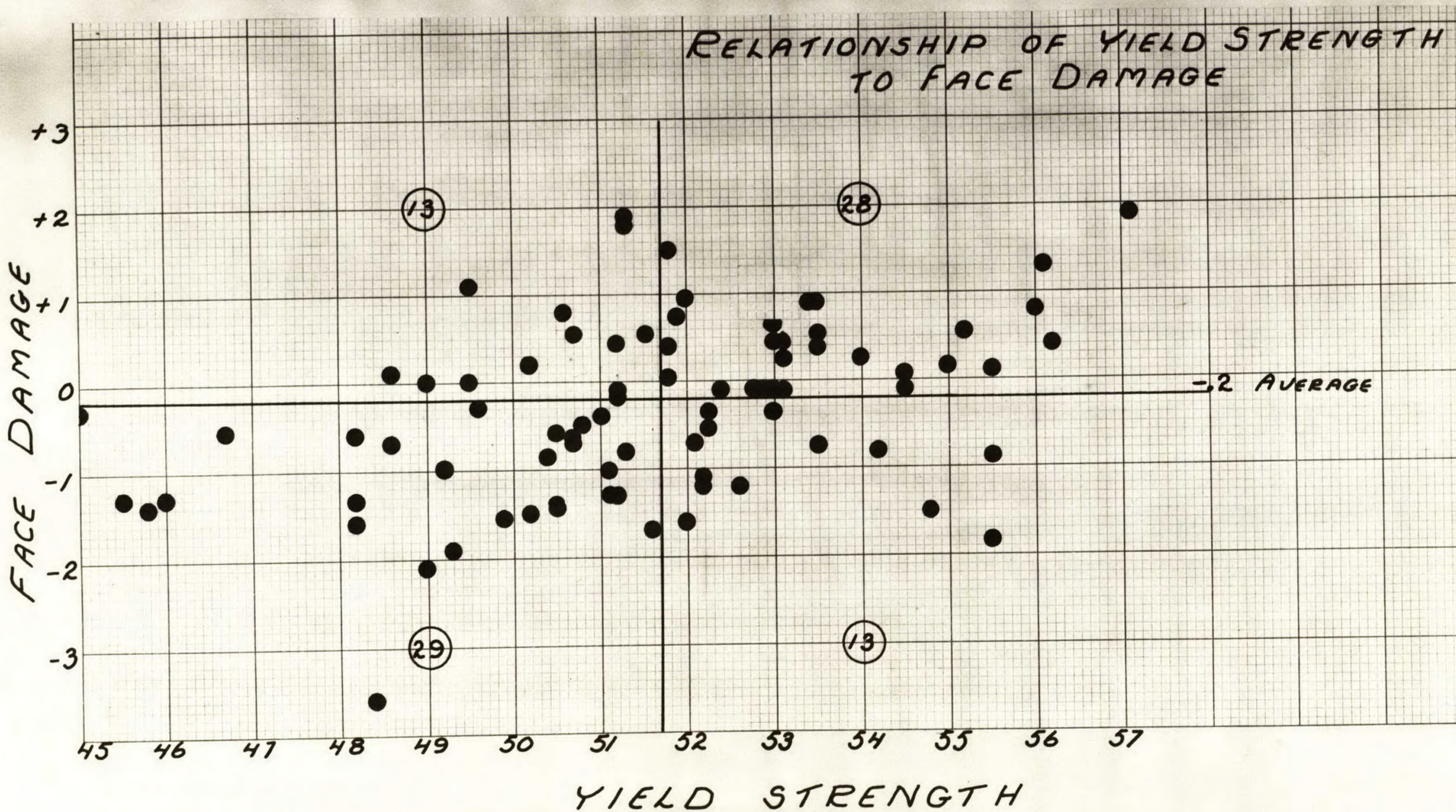
(Pages 40 and 41 are)
(full-page charts.)

CHART FOR DETERMINING SIGNIFICANCE OF VARIATION FROM AVERAGE (X^2 TEST)




RELATIONSHIP OF YIELD STRENGTH
TO FACE DAMAGE
FACE DAMAGE
+3
+2
+1
0
-1
-2
-3
13
28
29
13
-.2 AVERAGE
45
46
47
48
49
50
51
52
53
54
55
56
57
YIELD STRENGTH

APPENDIX C. - GROUPING LIST (Groups of 2).

Group No.	Plate No.	Group No.	Plate No.
1.	R3 R4	12.	R26 R27
2.	R6 R7	13.	R28 R29
3.	R8 R9	14.	R30 R31
4.	R10 R11	15.	R32 R33
5.	R12 R13	16.	R34 R35
6.	R14 R15	17.	R36 R37
7.	R16 R17	18.	R38 R39
8.	R18 R19	19.	R40 R41
9.	R20 R21	20.	R42 R43
10.	R22 R23	21.	R44 R45
11.	R24 R25		

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APPENDIX D. - "n" VALUE.

A 10-mm. ball is used to indent a sample of steel with loads of 50, 100, 150, 250 and 300 kilograms. The diameter of the indentation is plotted against load on logarithmic paper. If the technique is satisfactory, all points will fall on a straight line. The slope of the line is 2.0 when indent-load conditions follow the Brinell Equation. If the slope is greater than 2.0, the material is a work-hardening metal. The test, therefore, gives a measurement of the work-hardening properties.

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APPENDIX E. - ANALYSIS OF VARIANCE TECHNIQUE APPLIED TO DEPTH OF DECARBURIZATION.

Depth of decarburization (x 0.1 mm.) of GOOD plates		Depth of decarburization (x 0.1 mm.) of BAD plates	
A	A^2	B	B^2
16.5	272.3	15.5	240.3
15.0	225.0	14.0	196.0
15.0	225.0	15.0	225.0
21.5	462.3	14.0	196.0
16.0	256.0	12.5	156.3
14.5	210.3	16.0	256.0
15.0	225.0	12.0	144.0
17.5	306.3	16.0	256.0
16.5	272.3	15.0	225.0
13.5	182.3	15.0	225.0
14.5	210.3	13.5	182.3
13.5	182.3	14.0	196.0
14.0	196.0	14.5	210.3
		11.0	121.0
203.0	3,225.4	198.0	2,829.2

Symbols Used:

Σ = the sum of

Na = the number of test values in Column A.

Variation in Column A:

$$\Sigma A^2 - \frac{(\Sigma A)^2}{Na}$$

ΣA^2 = 3,225.4
ΣA = 203
Na = 13

Column A variation -

$$3,225.4 - \frac{(203)^2}{13} = 55.5.$$

Variation in Column B:

$$\Sigma B^2 - \frac{(\Sigma B)^2}{Nb}$$

ΣB^2 = 2,829.2
ΣB = 198
Nb = 14

Column B variation -

$$2,829.2 - \frac{(198)^2}{14} = 29.$$

(Appendix E, cont'd) -

Variation Between Columns:

$\bar{\bar{X}}$ = average of all results = 15.61.

$\bar{A}$ = average of Column A.

$\bar{B}$ = average of Column B.

Variation between columns -

$Na(\bar{\bar{X}} - \bar{A}) - Nb(\bar{\bar{X}} - \bar{B})^2$

$13(15.61 - 14.85)^2 + 14(14.85 - 14.14)^2 = 14.55.$

Total Variation:

$$\text{Sum of all squares} = \frac{(\text{sum of all values})^2}{\text{number of test values}}$$

$$= 3,225.4 + 2,829.2 - \frac{(203+198)^2}{1.3+14} = 99.01.$$

VARIATION:

The term "variation" as used in statistics means the sum of squared deviations from the average. A check on the calculation of variation is made, as follows:

Variation in Column A	-	55.5
" " " B	-	29.0
Variation between columns	-	14.55
Total	-	99.05

Note that the total variation is the sum of variations within columns and between columns.

The problem is to find whether variation between columns is significantly greater than variation within columns. This is done by calculation of variance.

VARIANCE:

$$\text{Variance} = \frac{\text{variation}}{\text{degrees of freedom}}$$

With 27 results in two columns two degrees of freedom are lost, because there is an average established for each column.

(Continued on next page)

(Variance, cont'd) -

Source of variation		Variation	Degrees of freedom	Variance
Within columns	-	84.5	(27-2)	3.38
Between columns	-	14.55	(2-1)	14.55
Total variation	-	99.01	(27-1)	3.8

The variance between columns appears to be much greater than that within columns. Whether or not this is significant is determined by the Z test.

Z Test for Significant Difference:

$$Z = 1.15129 \log_e \frac{\text{variance between columns}}{\text{variance within columns}}$$

$$= 1.15129 \log_e \frac{14.55}{3.38}$$

$$= 0.729.$$

From tables in R. A. Fisher's book, "Statistical Methods for Research Workers," we find that when

degrees of freedom within column = 25,

degrees of freedom between columns = 1,

and Z = 0.722,

the odds are 95 out of 100 that the observed difference in column averages is significant. We are therefore justified in stating that DECARBURIZATION IS RELATED TO ARMOUR PLATE FAILURE. AS DECARBURIZATION INCREASES ARMOUR QUALITY IMPROVES WITHIN THE LIMITS INVESTIGATED.

The Analysis of Variance method requires much more work than the Chi-Square system. However, it is more accurate and is applied in doubtful cases.

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