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R E P O R T

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1400.

Dominion Foundries and Steel 60-mm. Armour Plate: Final Report on Correlation Between Chemical and Physical Tests and Ballistic Limit.

(Copy No. 30.)

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Abstract.

Some time in 1940 the hypotheses were advanced that -

(A) FOR EACH VARIABLE IN THE ARMOUR-MAKING PROCESS AN OPTIMUM RANGE PROBABLY EXISTS;

(B) IF ALL VARIABLES WERE HELD IN THEIR OPTIMUM RANGE THE MAXIMUM ATTAINABLE QUALITY OF ARMOUR FOR EACH PARTICULAR PROCESS WOULD BE PRODUCED.

Before hypothesis A could be proven it was necessary

(Abstract, cont'd) -

to demonstrate that correlation between a variable (such as, say, phosphorus content) and ballistic limits could be found.

Several reports already issued by these Laboratories[*] deal with the method of proving that a correlation exists. Laboratory-type research[**] could not be applied; therefore, a system of analysing production data was developed with the assistance of Lieut.-Col. L. E. Simon of the Ballistics Research Laboratories, Aberdeen Proving Ground, Aberdeen, Md.

The findings to date apply only to chemical analysis and physical tests of D.F. & S. 60-mm. rolled armour plate. The bounderies of optimum ranges for the different variables were found, as follows:

Carbon, per cent	=	0.27-0.31
Silicon, "	=	0.30 min.
Sulphur, "	=	Not less than 0.015.
Phosphorus, "	=	Not less than 0.020.
Chromium, "	=	Not over 2.50.
Molybdenum, "	=	Not over 0.60.
Grossman hardenability	=	15 inches max.
Tensile strength, p.s.i.	=	140,000 minimum.
Yield strength, p.s.i.	=	115,000 minimum.
Elongation, per cent	=	0.20-0.21
Izod impact, foot pounds	=	62 maximum.
Brinell hardness	=	300 minimum.

In 231 heats during a two-year period, the indicated ranges coincided with the above average ballistic

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[*] Reports of Investigations Nos.:

1144: Armour Plate Improvement as Related To Statistical Analysis of Manufacturing Data. (January 9th, 1942).

1163: A Statistical Analysis of 60-mm. Armour Plate from the Dominion Foundries and Steel Limited. (May 1st, 1942).

1235: Quality Control: Engineering Science Applied to Inspection Practice. (June 1st, 1942).

1298: Dominion Foundries and Steel Limited 60-mm. Armour Plate Ballistic Limit Test Results Presented in Quality Control Chart Form. (September 19th, 1942).

1319: Hardenability of 60-mm. Armour Plate (Dominion Foundries and Steel), and its Relationship to Ballistic Limit. (October 30th, 1942).

[**] Hold all variables constant but one and observe the effect of its variation.

(Abstract, cont'd) -

limits.

It has been successfully demonstrated that it is possible to find the optimum ranges for variables in the armour-making process. The variables studied are probably only of secondary importance. The most important factors influencing the property of armour are generally agreed to be melting, ingot treatment, and heat treating. If observations in these three parts of the process were made, it is quite probable that very useful information on the control of armour properties could be obtained. This practice has been followed elsewhere and is strongly recommended as a project for Canadian armour research.

Statistical Method:

Laboratory research method consists in controlling all conditions but one and observing the effect of its variation. From the results of these experiments general laws are deduced and application to industry recommended.

The statistical method is designed to find the effect of one variable even though all other variables are not held constant. Thus research can be carried out on industrial processes while they are in operation. The statistical method is made possible by what are commonly known as the Laws of Large Numbers.

The first examples of industrial research using statistical method on steel processes were published by Karl Daeves in 1924. At present most industrial research projects make some use of statistical method.

The following example shows how optimum Brinell

(Statistical Method, cont'd) -

hardness was determined for the available data.

EXAMPLE -

Records of Brinell hardness and ballistic limit for 72 armour plates were plotted as in Figure 1.

A rational observer would draw several conclusions at this point:

(1) The nature of the process is such that ballistic limit values fluctuate between 1850-1950, and Brinell hardness values between 265-312.

(2) If the Brinell hardness were held constant at any value, the ballistic limit would still vary over a range of 150 f.p.s.

(3) Control of armour quality through Brinell hardness alone would not be very effective.

(4) There are other variables fluctuating even when Brinell is constant.

The question to be answered is: "Is there any indication of an optimum range for Brinell?" The method proposed is to divide the scattering of dots into three groups by vertical lines, and into two groups by a horizontal line. This has been done in Figure 2.

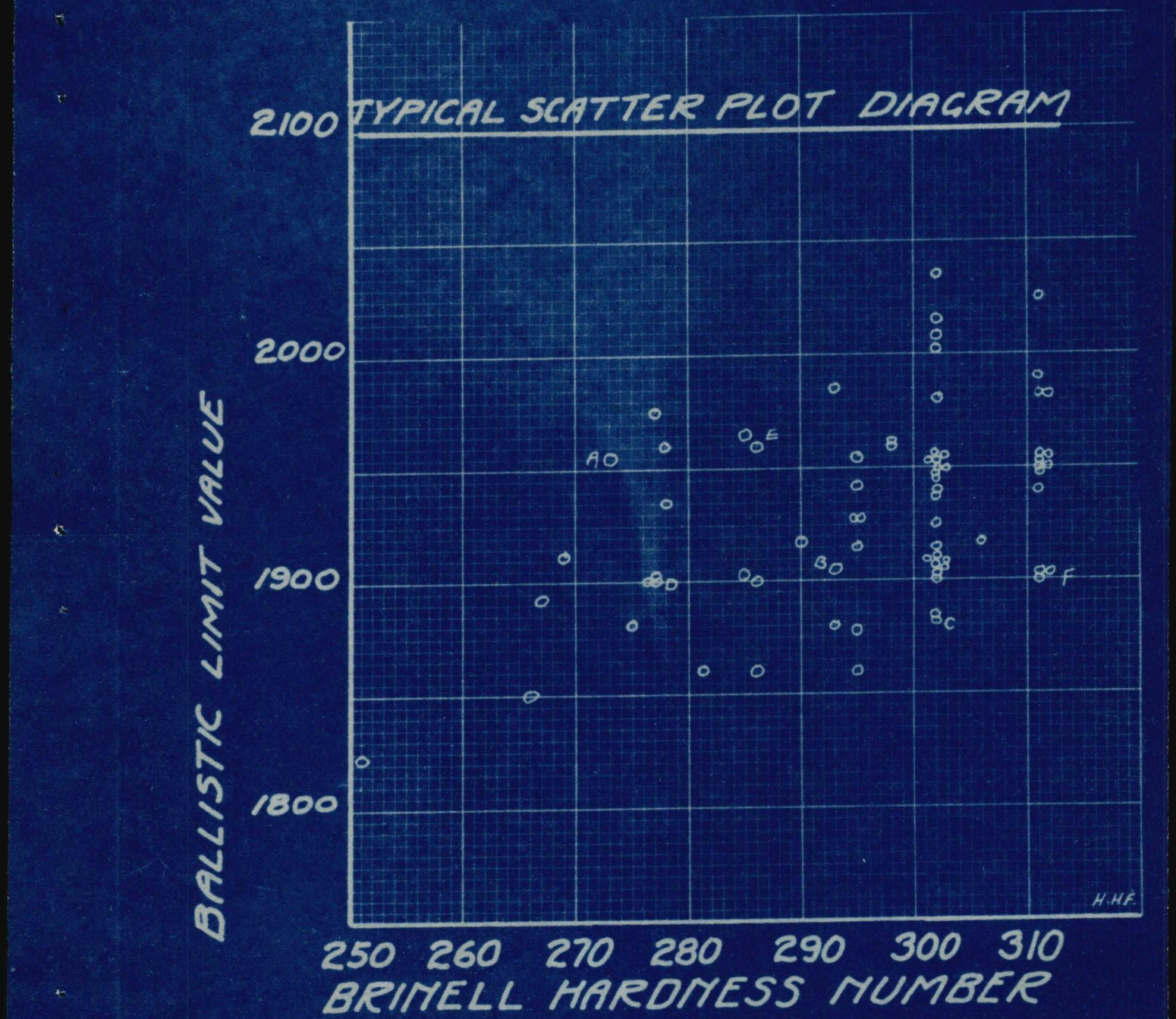
From this division we obtain three ratios.

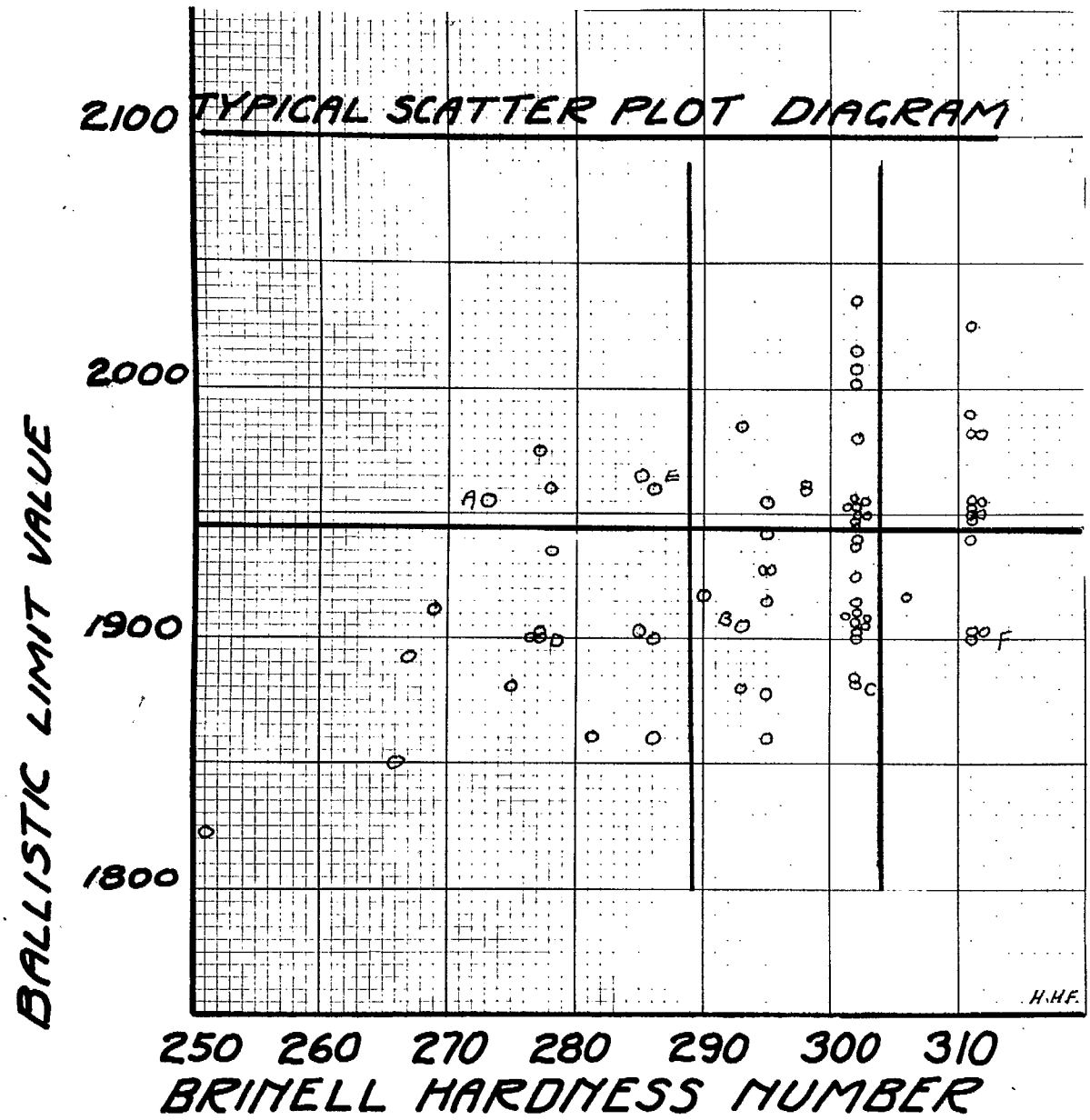
Table I.

		Brinell 250-289	Brinell 290-304	Brinell 305-313
Number above 1945	=	5	17	10
Number below 1945	=	13	22	5
Ratio above 1945	=	$\frac{5}{18}$	$\frac{17}{39}$	$\frac{10}{15}$
Per cent above 1945	=	28	43.5	67

(The following pages contain
Figures 1, 2, and 3.
Text continues on Page 8.)

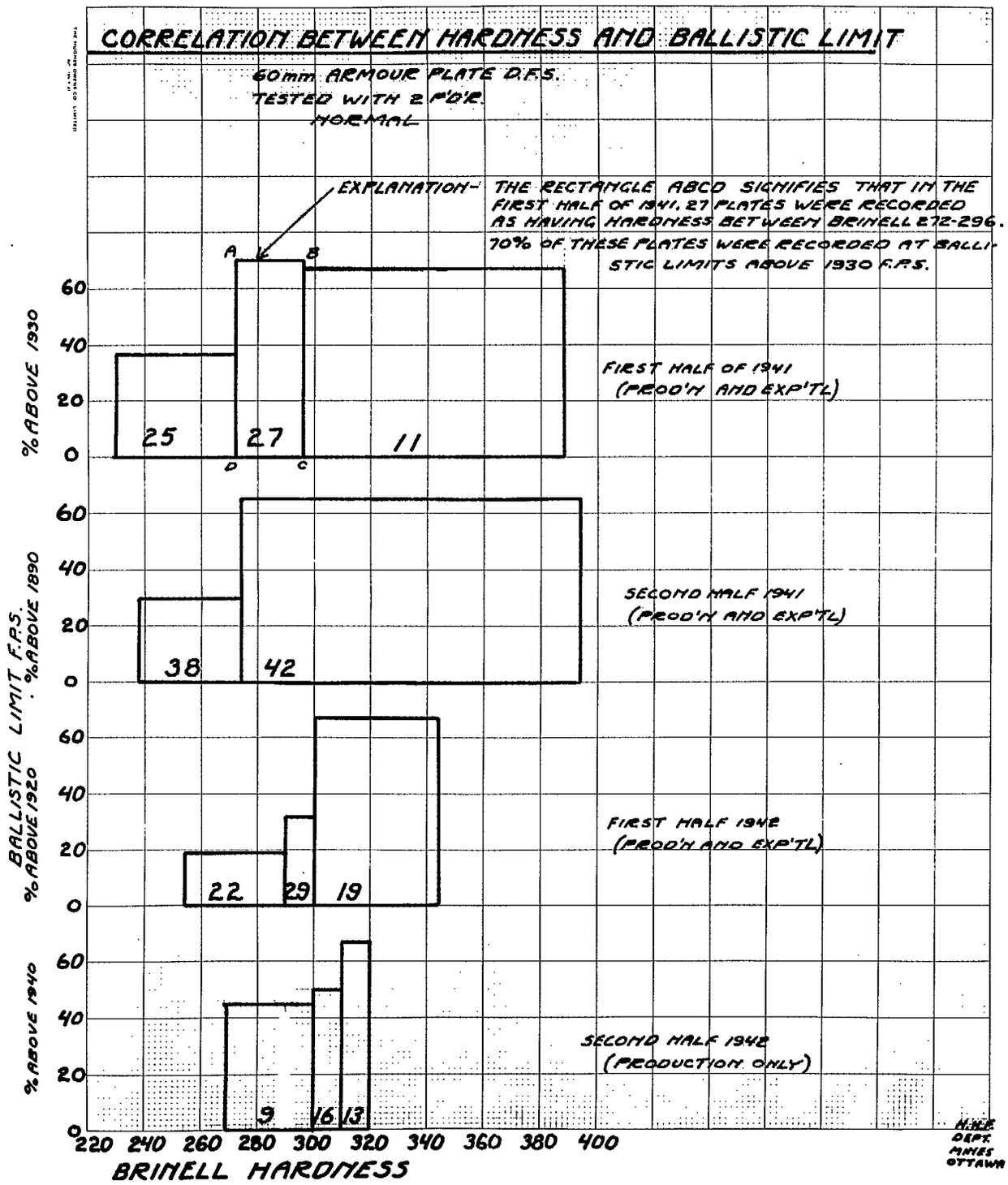
TYPICAL SCATTER PLOT DIAGRAM




TYPICAL SCATTER PLOT DIAGRAM
BALLISTIC LIMIT VALUE
2100
2000
1900
1800
250 260 270 280 290 300 310
BRINELL HARDNESS NUMBER
A
B
C
E
F
H.H.F.

CORRELATION BETWEEN HARDNESS AND BALLISTIC LIMIT

60mm ARMOUR PLATE D.F.S.
TESTED WITH 2 P'D'R.
NORMAL



M.N.E.
DEPT.
MINES
OTTAWA

(Example, cont'd) -

The cautious individual will immediately point out that although a higher percentage of above-average ballistics occurs in the 305-313 Brinell range, such an event might be due to coincidence. This possibility must be investigated before any statement can be made. Are the ratios $\frac{5}{18}$ $\frac{17}{35}$ and $\frac{10}{16}$ indicative of random order or of purposive order?

The theoretical technique of determining the significance of ratio differences can be found in standard statistical texts. Report of Investigation No. 1395, "Field Trial Interpretation," dated May 1st, 1943, gives charts from which ratio differences can be evaluated.

The practical proof of the validity of the inference in Table I can be obtained as more data are collected. Figure 3 shows how four successive periods of ballistic-limit-Brinell records were plotted from data similar to Table I.

(Continued on next page)

(Example, cont'd) -

Note that the tendency for higher Brinell numbers to coincide with higher ballistic values is evident over four successive six-month periods.

From Figure 5 it seems logical to conclude that the lower boundary of Brinell for optimum ballistic limit is 300. The upper limit remains as yet undetermined.

The upper limit, of course, is determined by the overproofing shock test, another criterion for armour quality.

Theory of Large Numbers:

The large number method makes it possible to determine the effect of one variable on a product even though many other variables are fluctuating.

When heats of steel are divided into groups according to Brinell hardness, as in Table I, the variation other than Brinell is essentially the same in each group. The larger the number involved, the more identical the groups will become.

Thus, from production data three groups of heats, similar in all respects except Brinell hardness, are obtained. It is then possible to find the relationship between Brinell and ballistic limit.

Associated Variables:

Since four successive six-month periods show the same relationship between many variables and ballistic limit, the Theory of Large Numbers is substantiated in a practical manner. However, it has been pointed out that the three hardness classes the heats are not truly identical since hardness

(Associated Variables, cont'd) -

is related to tensile strength, carbon content, micro-structure, and processing variables. Actually, therefore, it would be more precise to state that the groups are identical except for the chosen variable and its associated variables.

Phosphorus grouping would also divide the heats according to melting practice, furnace charge, analysis, etc.

Consideration of associated variables must be left to the practical metallurgist who is to interpret and make use of the statistical findings.

The charts in the appendix are all derived by the same method, as shown in the foregoing example.

DISCUSSION OF RESULTS:

Contrary to pre-war belief, increasing alloy content does not continue to increase armour quality. Over 15 inches Grossman hardenability a noticeable decline in ballistic properties is evident. This is presumably due to the sluggish nature of high alloy metal in heat treatment. With lower alloy a more homogeneous structure can be obtained.

The carbide-forming tendency of chromium over 2.50 per cent and molybdenum over 0.60 per cent is well known, and therefore it is not surprising to find maximum limits for these alloys.

Several steel melters were asked: "Why would a steel below 0.02 per cent phosphorus be lower in ballistic quality?" The general opinion seems to be that if the melt is over-oxidized with iron ore, the phosphorus will be lower than usual, and the bath will contain excessive oxides that are not wholly removed. A low melting temperature may coincide

(Discussion of Results, cont'd) -

with low phosphorus and other undesirable conditions.

Thus the correlation of phosphorus with ballistic limit gives a clue to melting practice.

If the variables in melting could be observed and recorded and then correlated with armour quality, valuable information might result.

Many steel plants employ metallurgical observers whose duty it is to observe and record in detail the history of each heat of steel. Analysis of the data leads to more efficient practice and a clearer understanding of the effect of steel-making operations on the final product. The work done on gun steel ingot practice is described in Report No. O.D. 34-3 from the Office of Scientific Research and Development (Washington, D.C.).

Unknown Influences:

The effectsof chemical and physical properties are minor in comparison with melting, ingot, and heat treat variables. Therefore, controlling chemicals and physicals in narrow ranges will not assure uniformity of armour plate quality. Some major factors influencing armour properties are:

Per cent iron ore in charge,
Length of melt down period,
Length of boil period,
Slag history,
Length of refining period,
De-oxidizing practice,
Tapping temperature,
Pouring temperature,
and so on.

If these and other factors were observed and recorded, more complete knowledge of optimum manufacturing

(Unknown Influences, cont'd) -

conditions could be obtained. Without the complete picture of the process, the information gained on chemical and physical tests is of little practical value.

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HHF:GHB.

(An appendix follows, comprising Pages 13 to 28.)

APPENDIX.

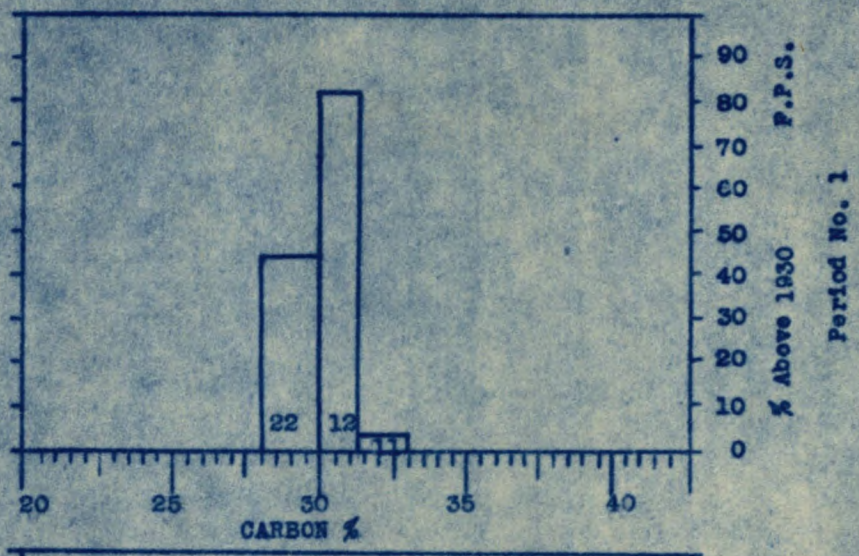
The following charts are a summary of the data used to determine optimum ranges for chemicals and physicals. Note that the oblongs represent groups of test results. The numbers in the oblongs indicate the number of tests in the group. The width of the base indicates the range of test values included in the group. The height of the oblong indicates the percentage of the group which was above average in ballistic limit.

Four six-month periods covering 1941 and 1942 were recorded. Experimental results were included with regular production plates in Periods 1, 2 and 3. Charts follow in this order, comprising Pages 14 to 28:

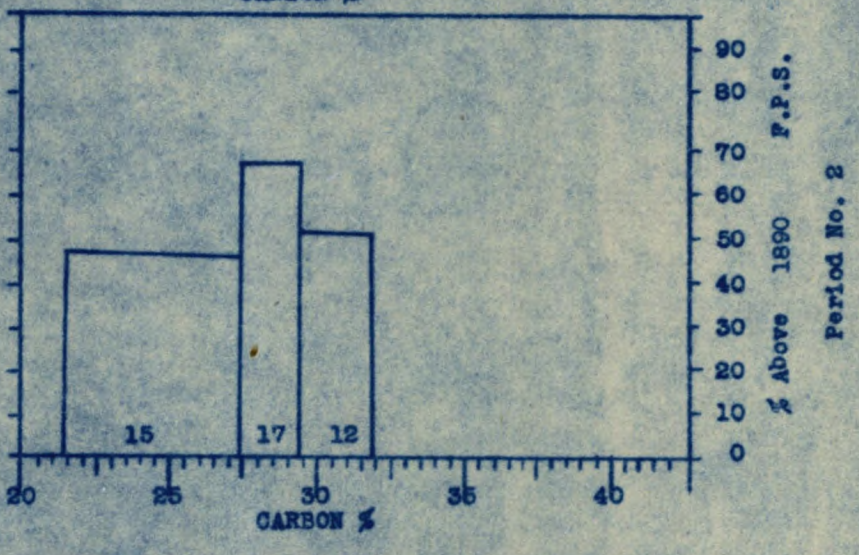
Carbon.
Manganese.
Silicon.
Sulphur.
Phosphorus.
Nickel.
Chromium.
Molybdenum.
Hardenability.
Tensile.
Yield.
Elongation.
Reduction in area.
Izod.

HHF:GHB.

CORRELATION BETWEEN CARBON AND BALLISTIC LIMIT
HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
WIDTH " " " SPREAD OF RESULTS
NUMBER IN " " " NO. OF RESULTS



Period No. 1



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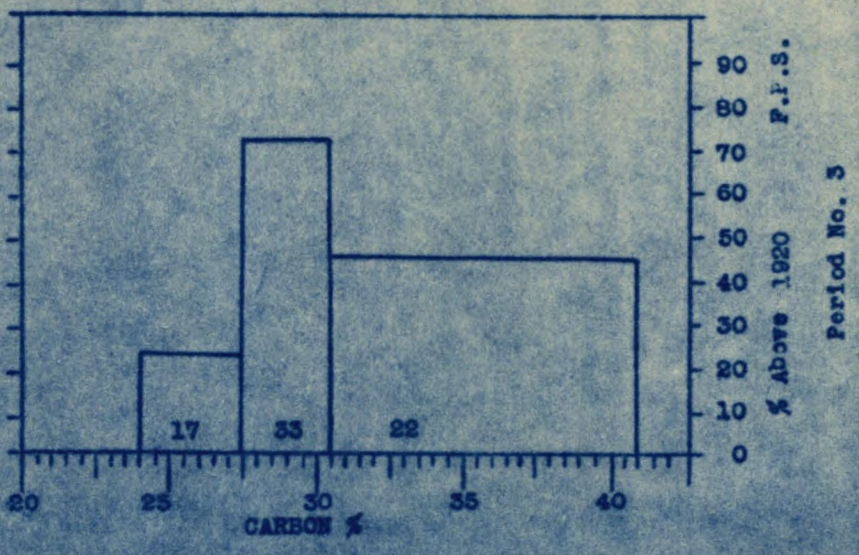

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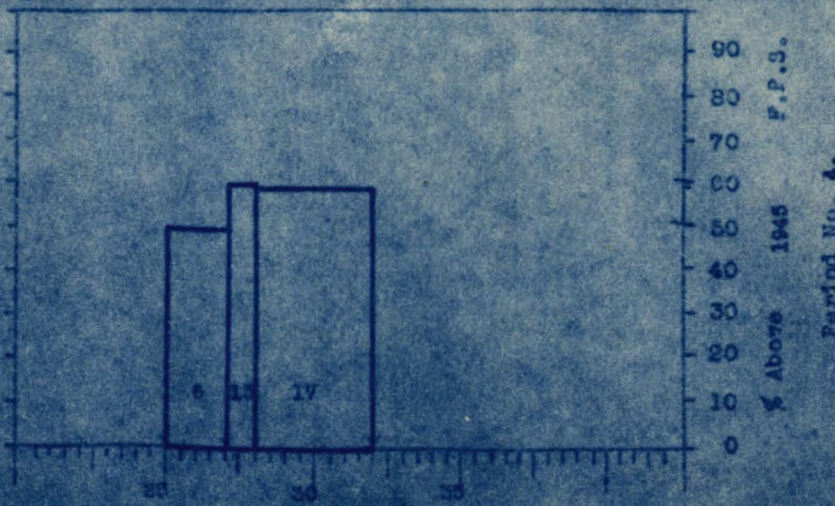
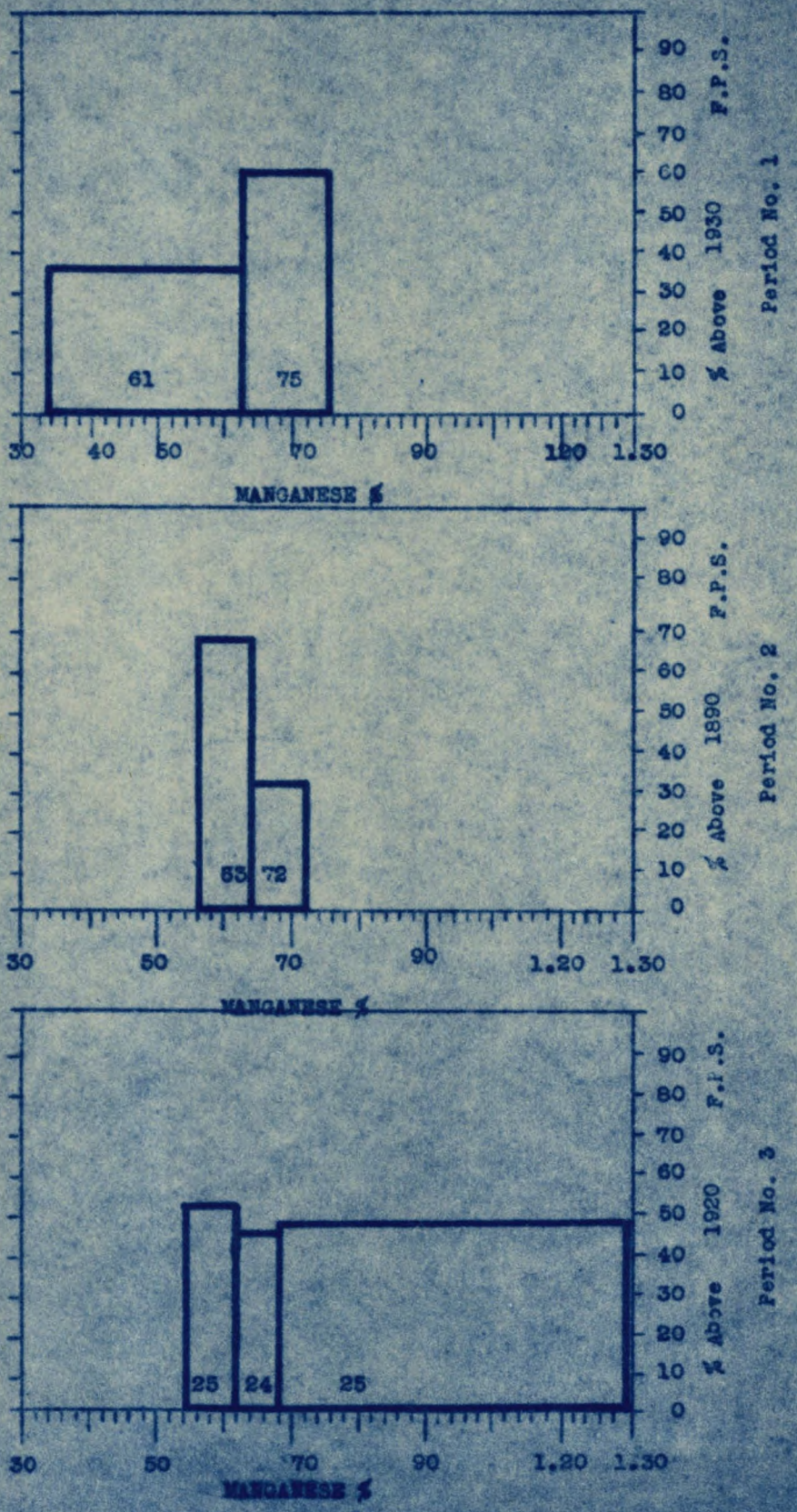
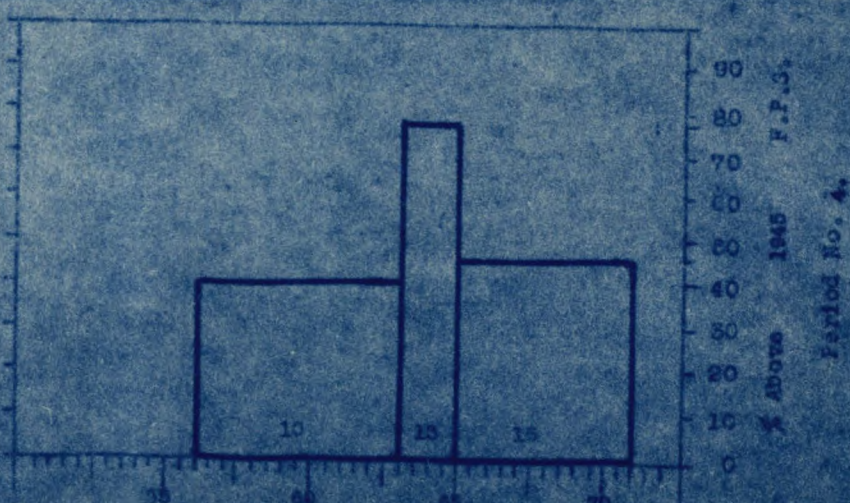


Period No. 4.

CORRELATION BETWEEN MANGAN. AND BALLISTIC LIMIT
HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
WIDTH " " " SPREAD OF RESULTS
NUMBER IN " " NO. OF RESULTS





CORRELATION BETWEEN SILICON AND BALLISTIC LIMIT
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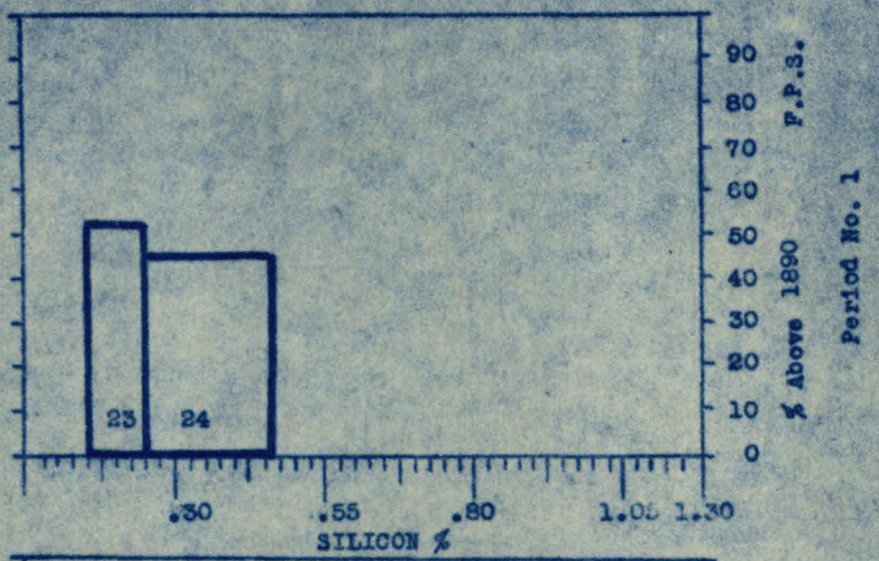
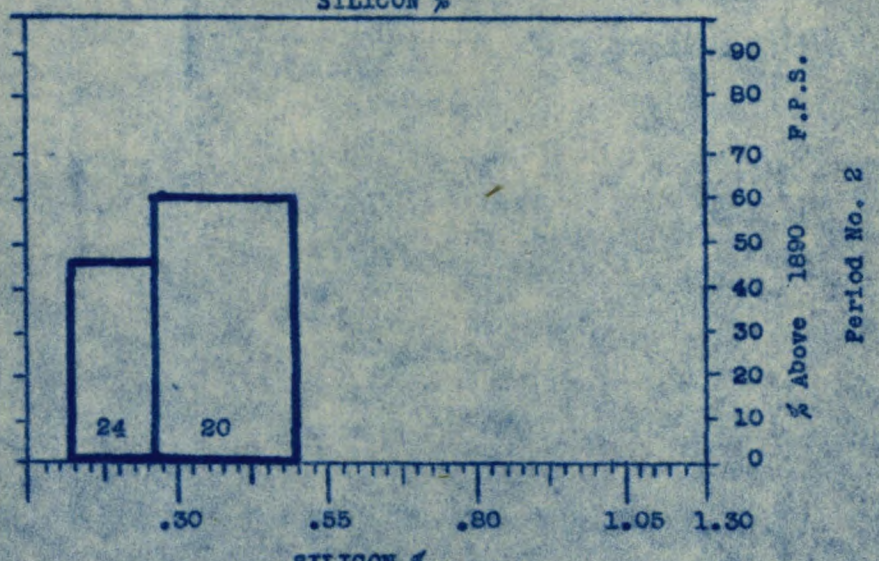
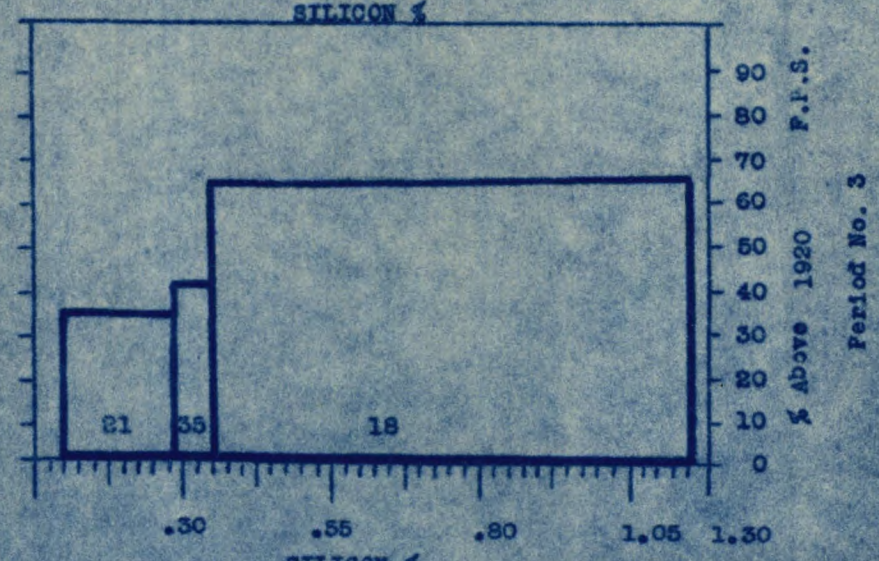
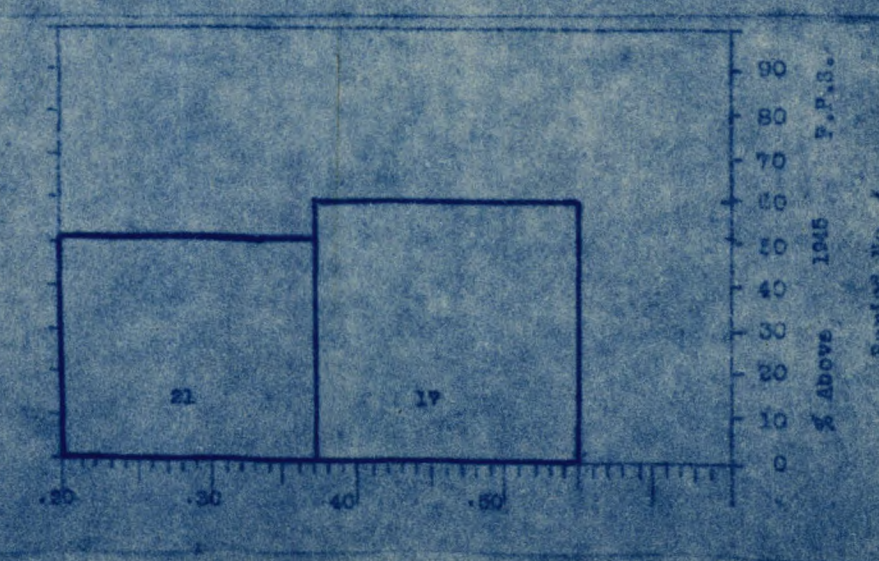
NUMBER IN " " NO. OF RESULTS

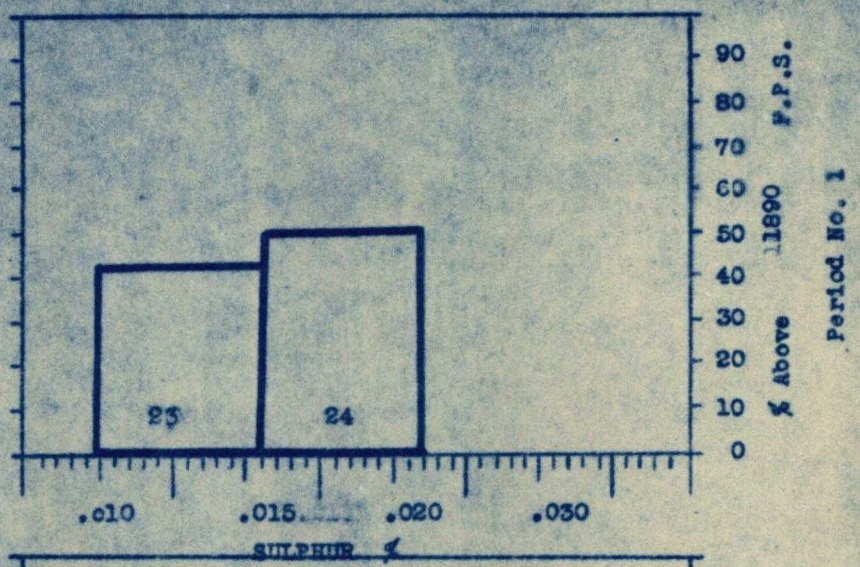


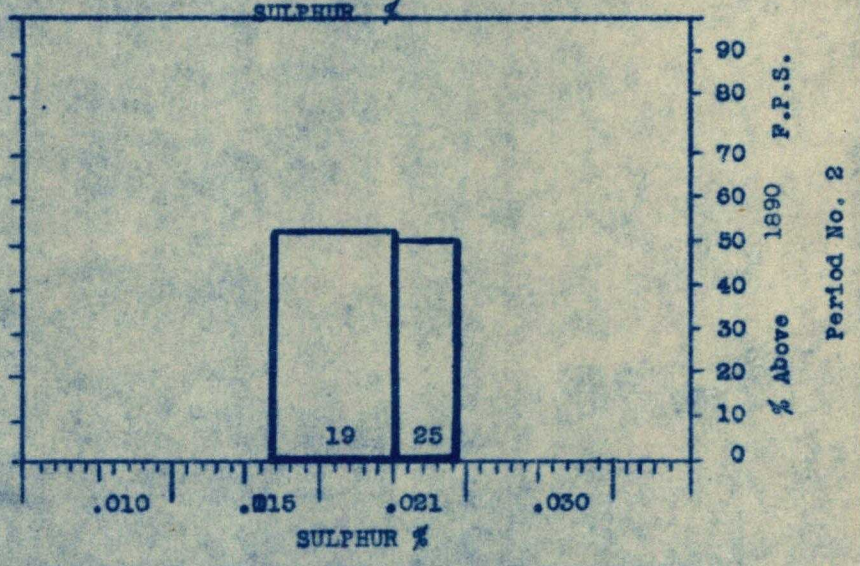


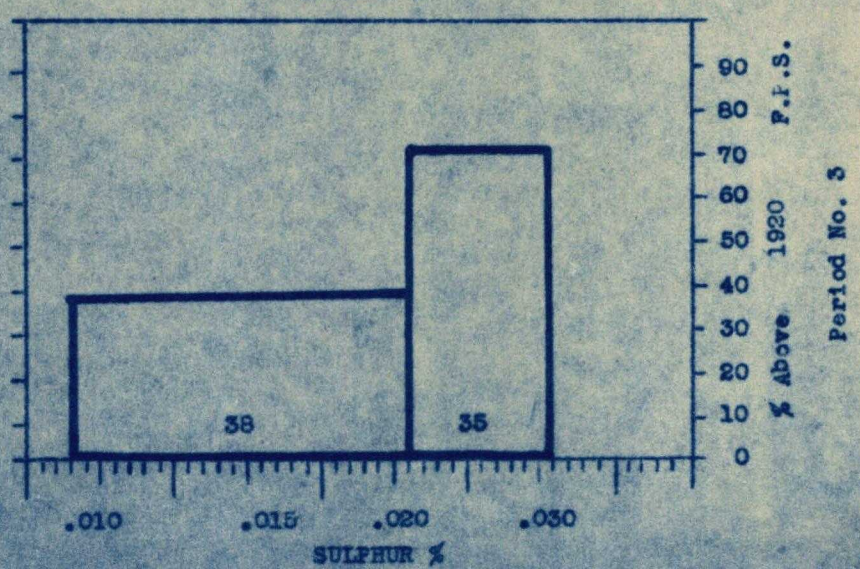


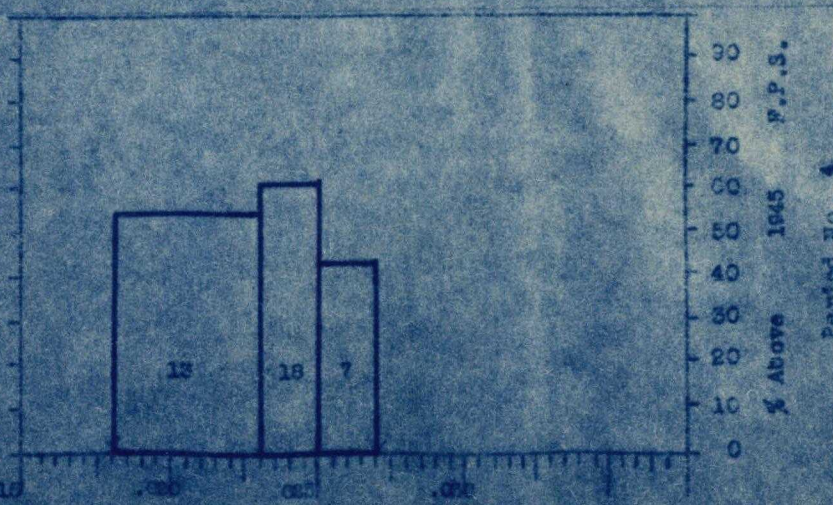


CORRELATION BETWEEN SULPHUR AND BALLISTIC LIMIT
HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
WIDTH " " " SPREAD OF RESULTS
NUMBER IN " " NO OF RESULTS









CORRELATION BETWEEN PHOS. AND BALLISTIC LIMIT

HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
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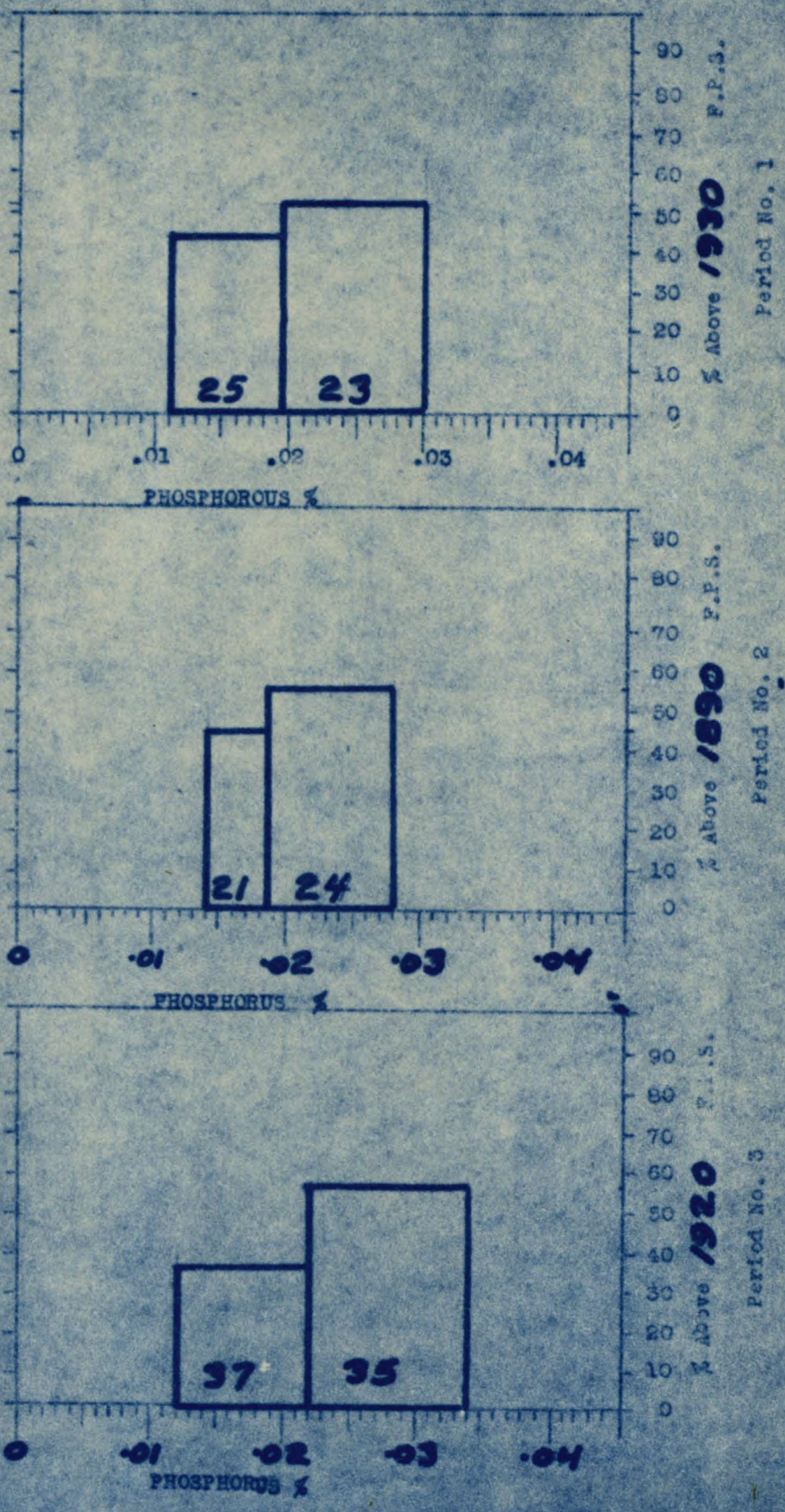
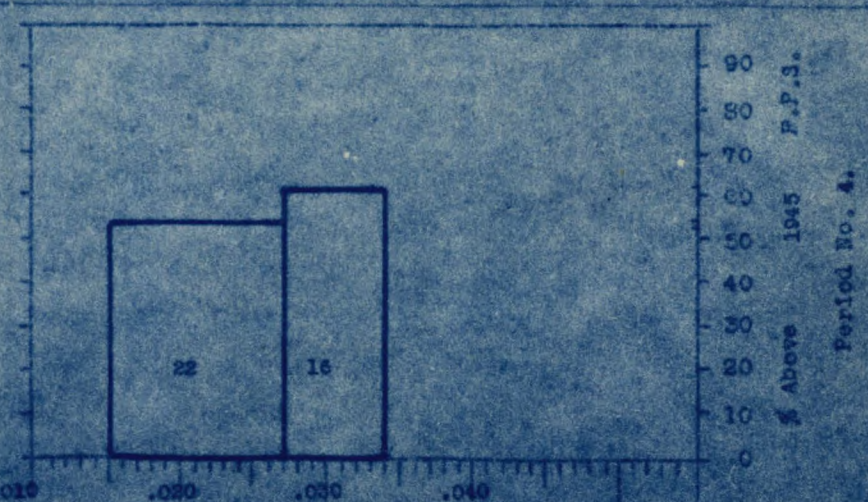
NUMBER IN " " NO. OF RESULTS





CORRELATION BETWEEN NICKEL AND BALLISTIC LIMIT
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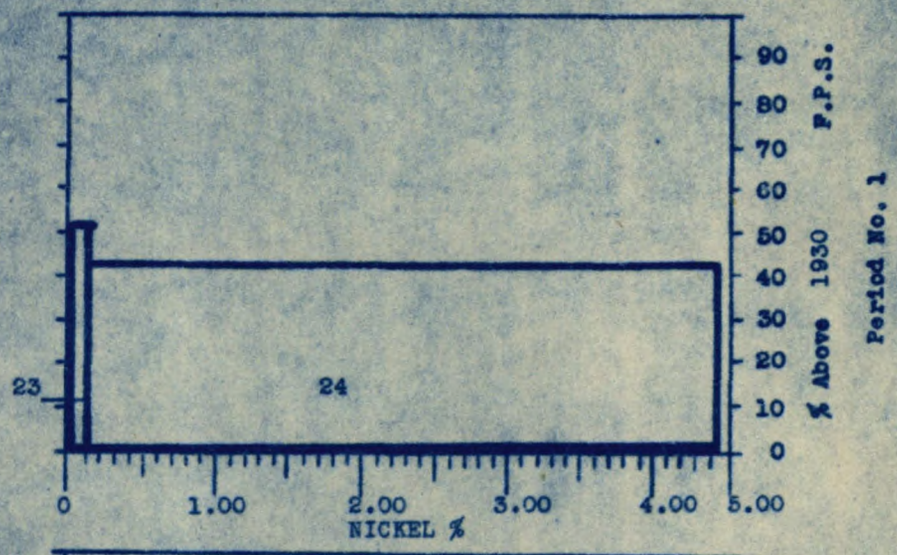

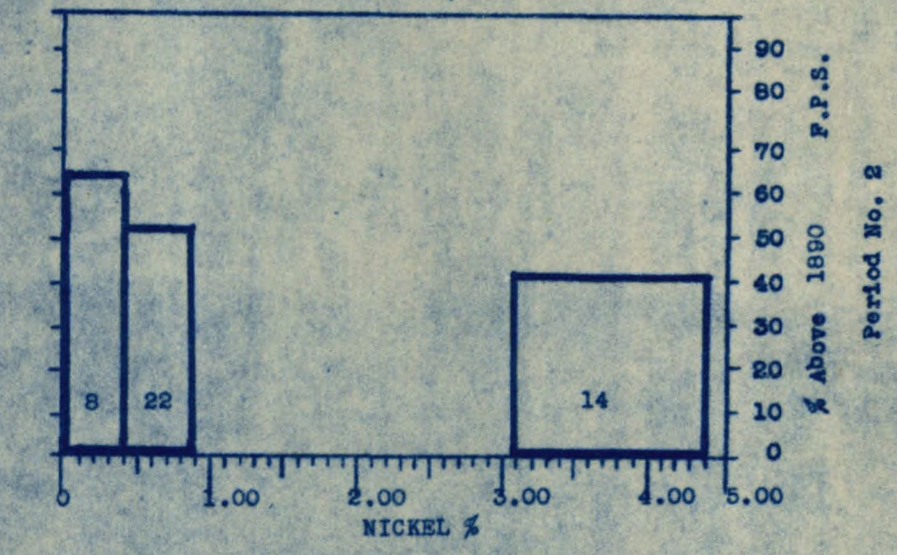

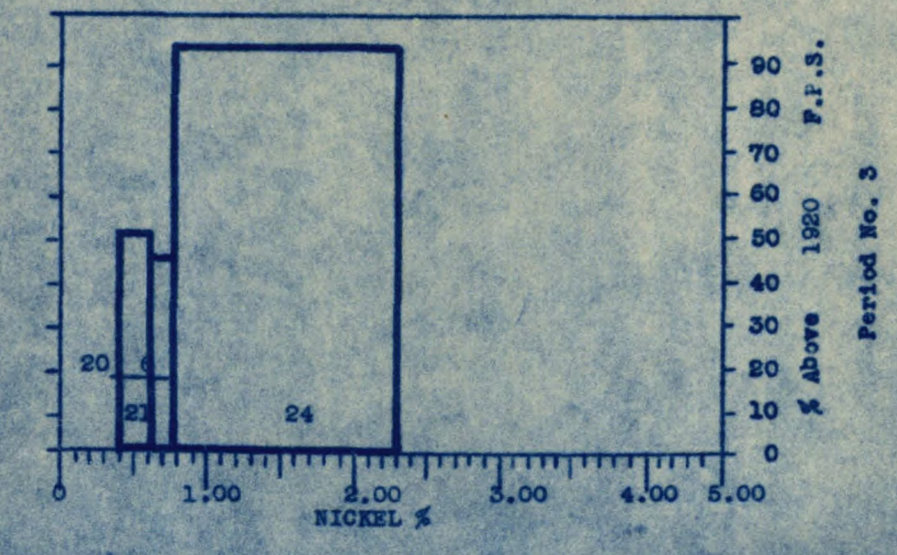

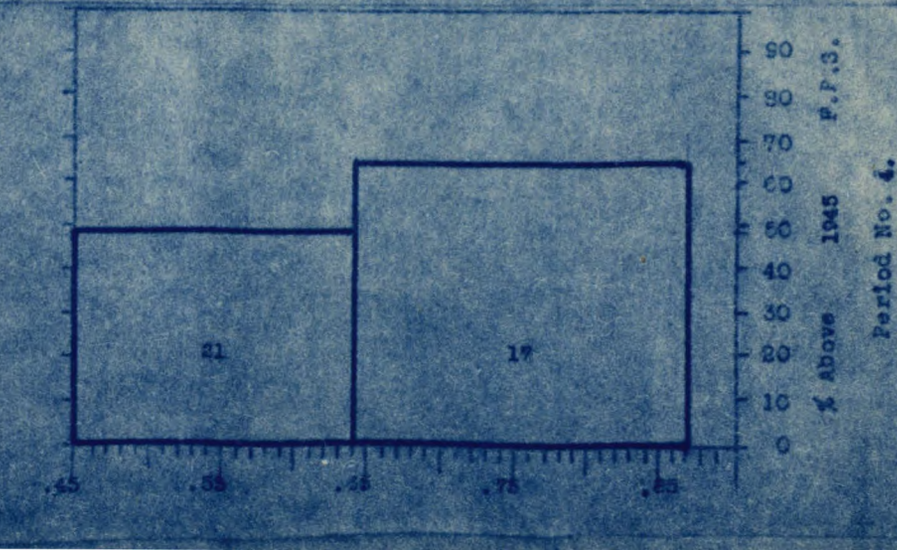

CORRELATION BETWEEN CHROM. AND BALLISTIC LIMIT

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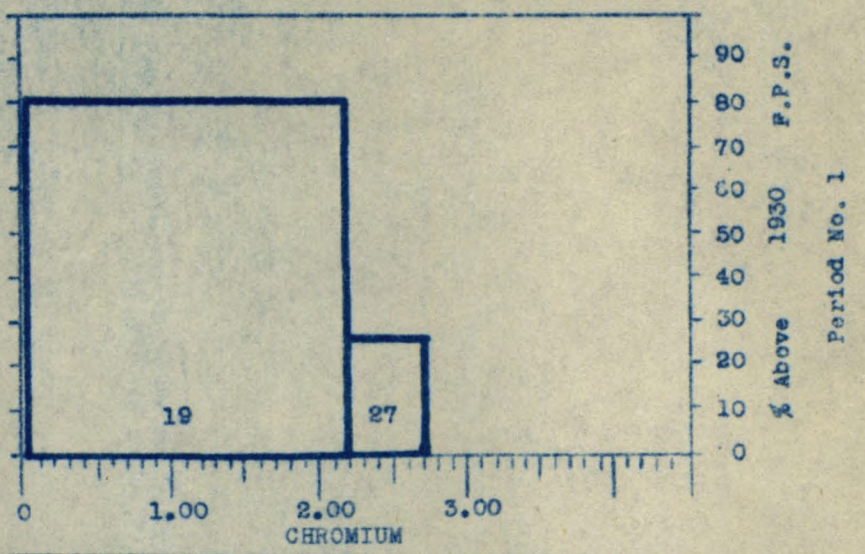
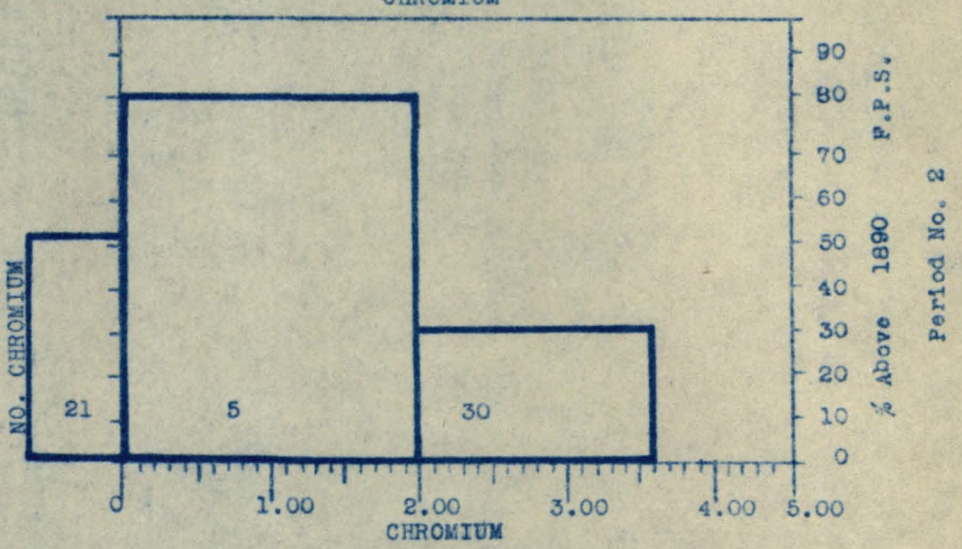
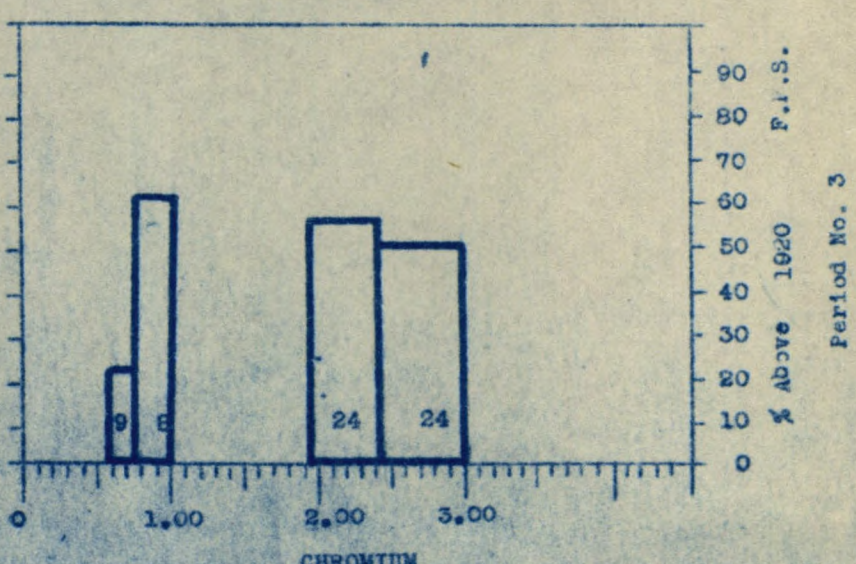
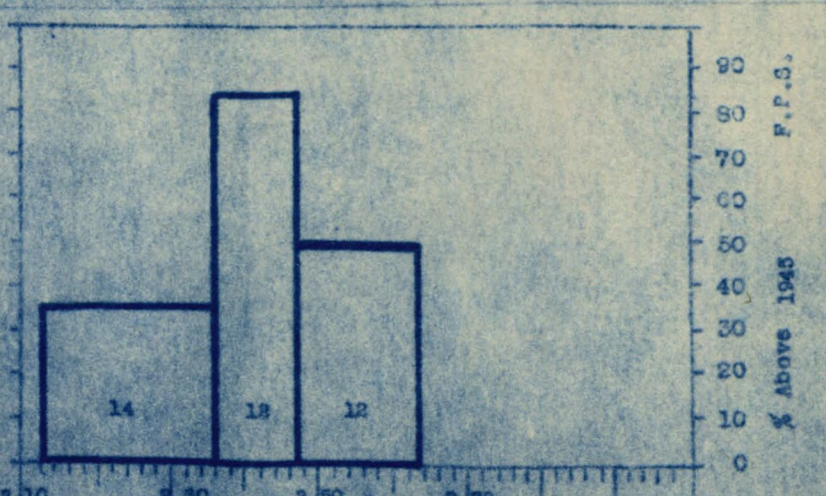
NUMBER IN " " NO. OF RESULTS









CORRELATION BETWEEN MOLYBD. AND BALLISTIC LIMIT
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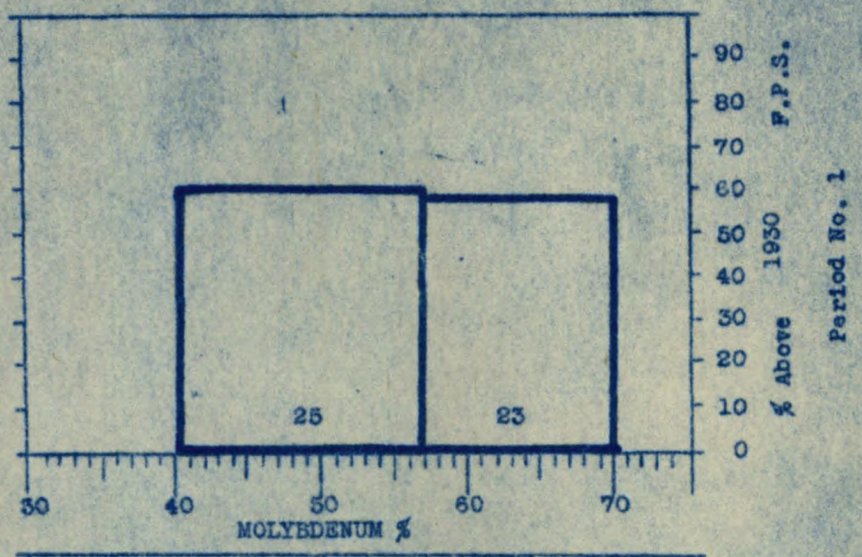
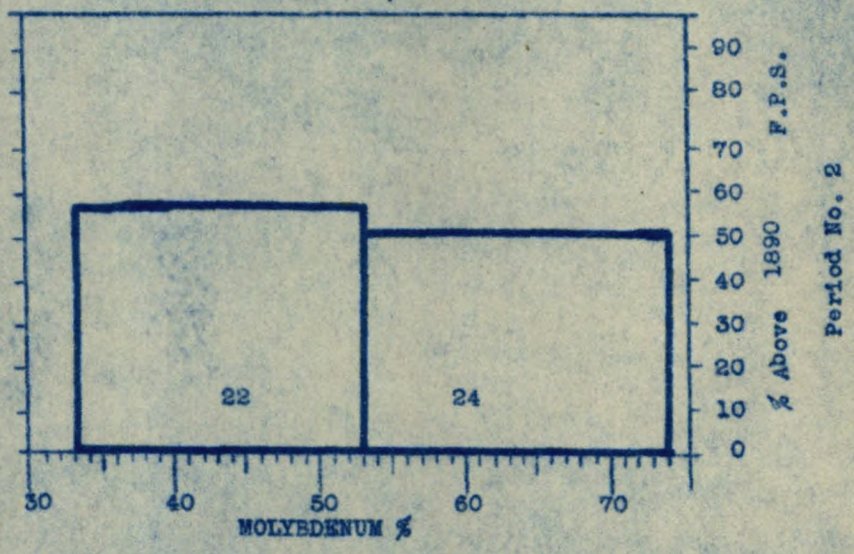
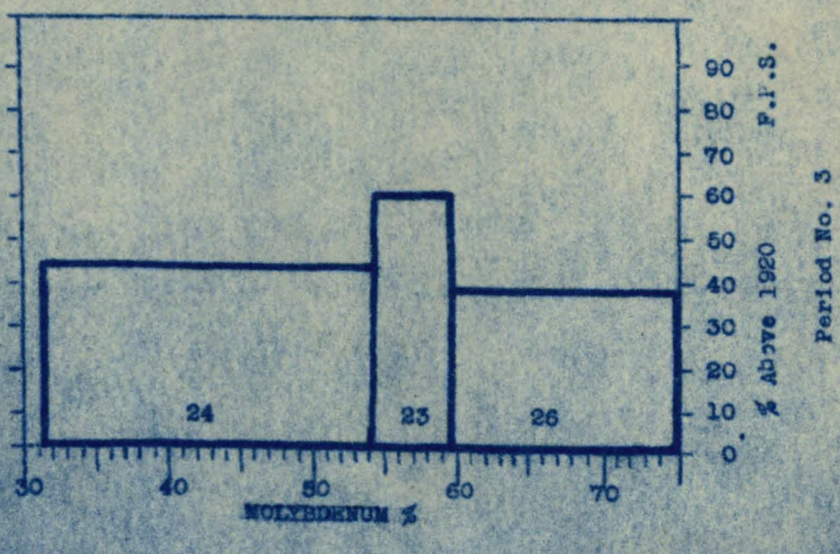
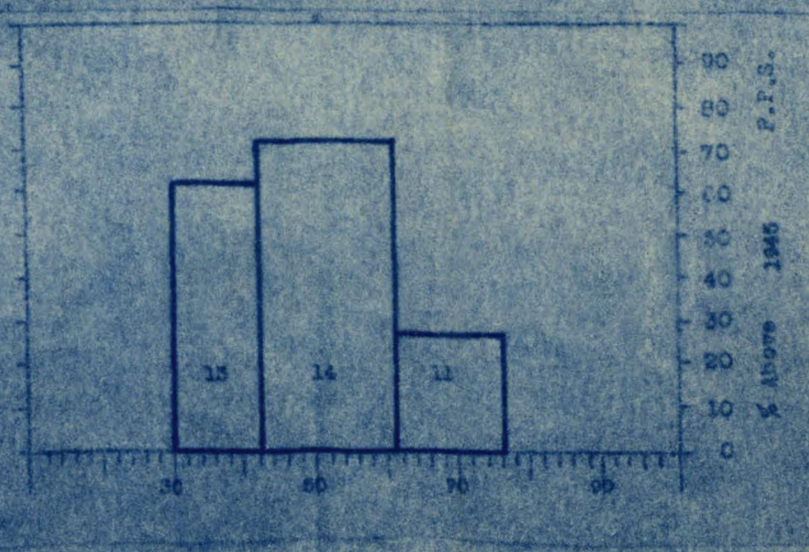
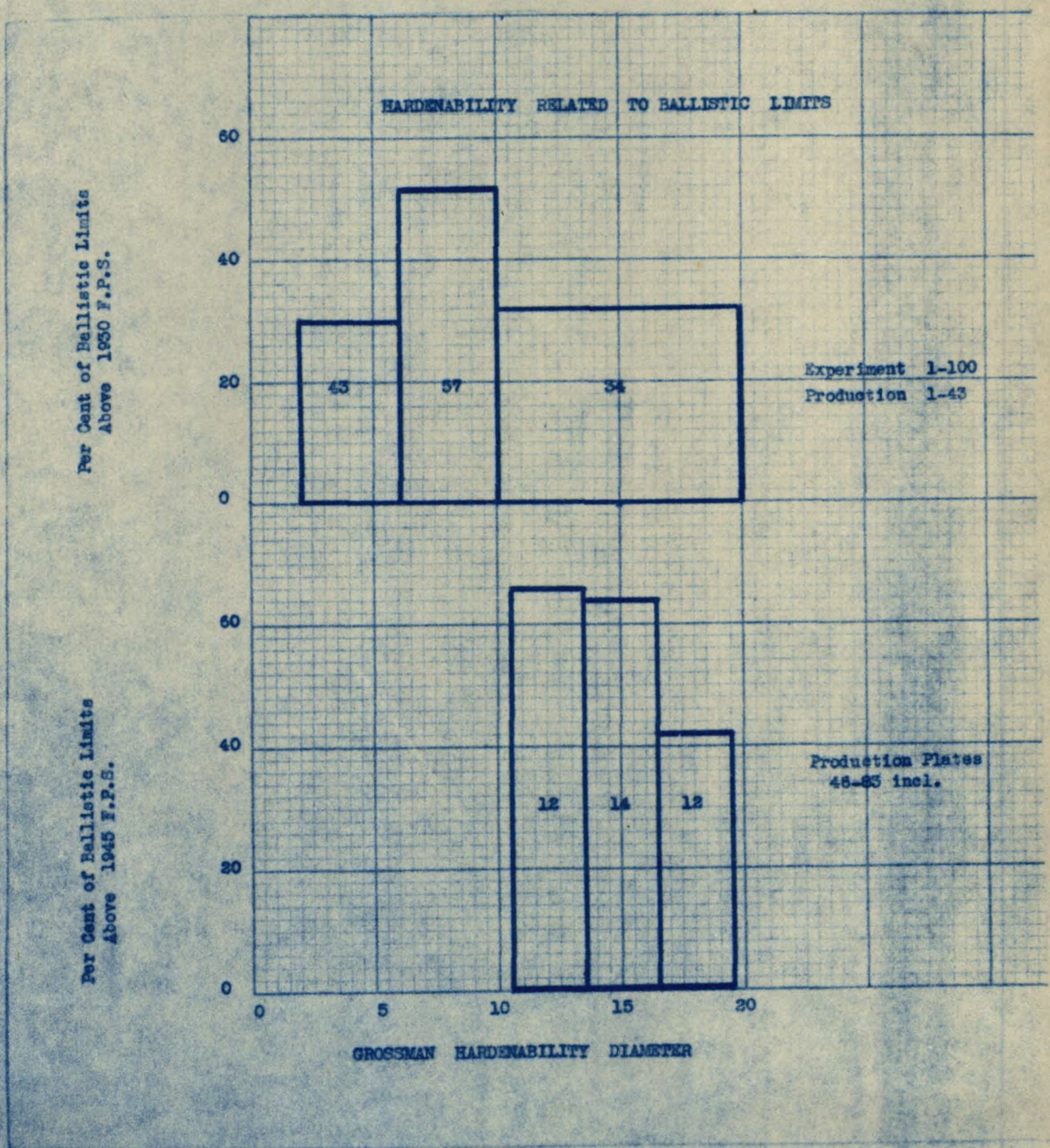
NUMBER IN " " NO. OF RESULTS



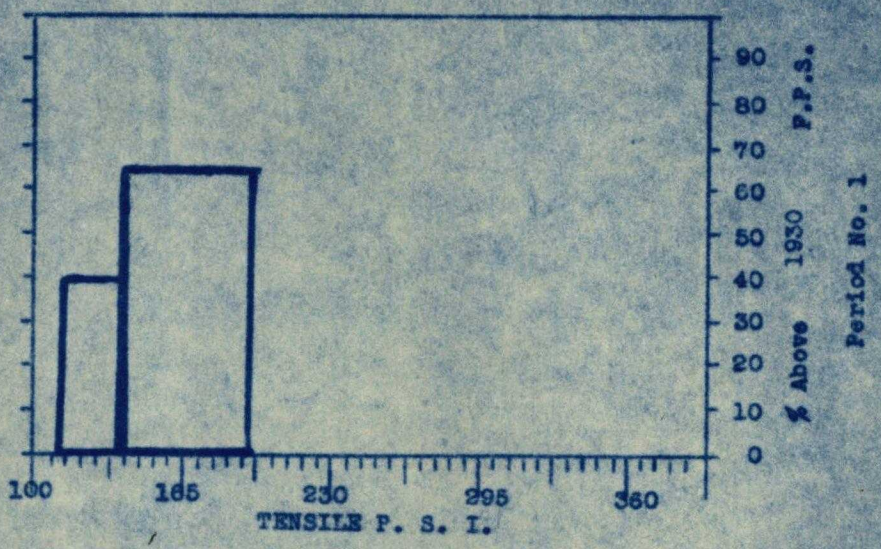


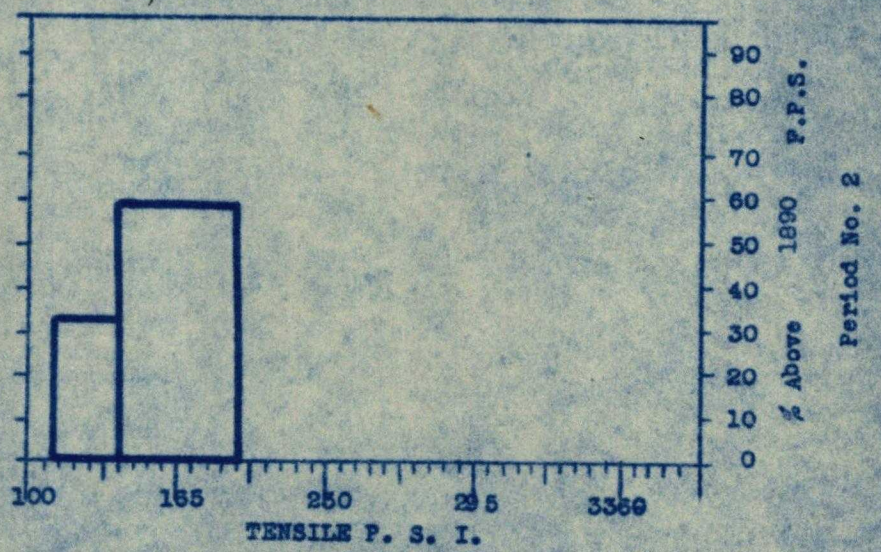


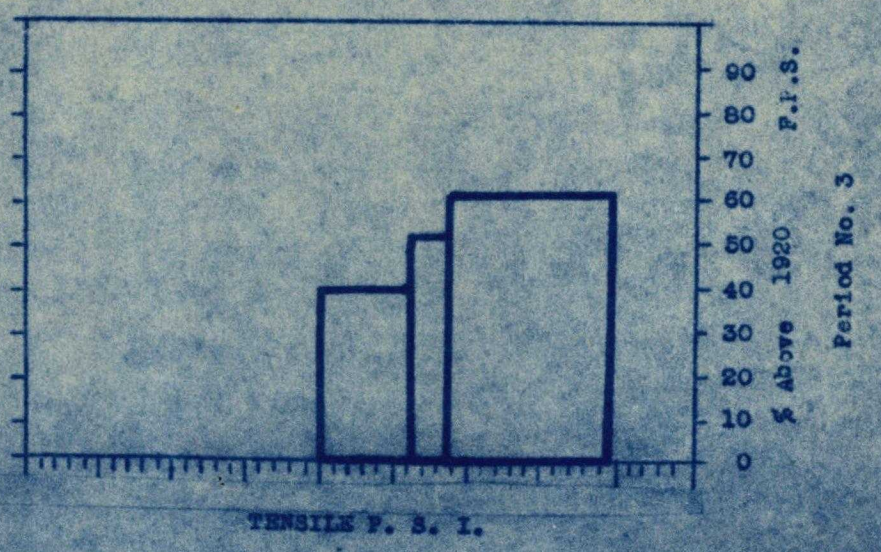


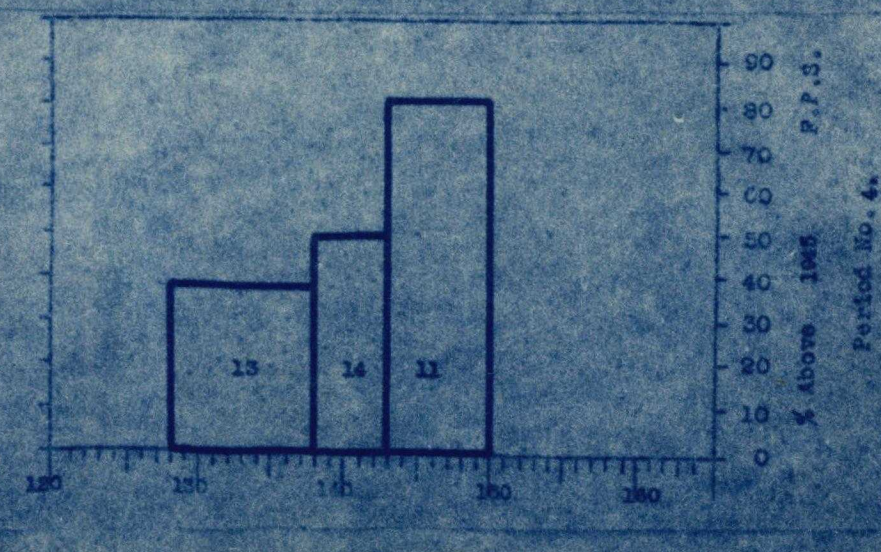

HARDENABILITY RELATED TO BALLISTIC LIMITS
Per Cent of Ballistic Limits
Above 1950 F.P.S.
60
40
20
0
43
57
34
Experiment 1-100
Production 1-43
Per Cent of Ballistic Limits
Above 1945 F.P.S.
60
40
20
0
12
14
12
Production Plates
46-83 incl.
0
5
10
15
20
GROSSMAN HARDENABILITY DIAMETER

CORRELATION BETWEEN TENSILE AND BALLISTIC LIMIT
HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
WIDTH " " " SPREAD OF RESULTS
NUMBER IN " " NO. OF RESULTS

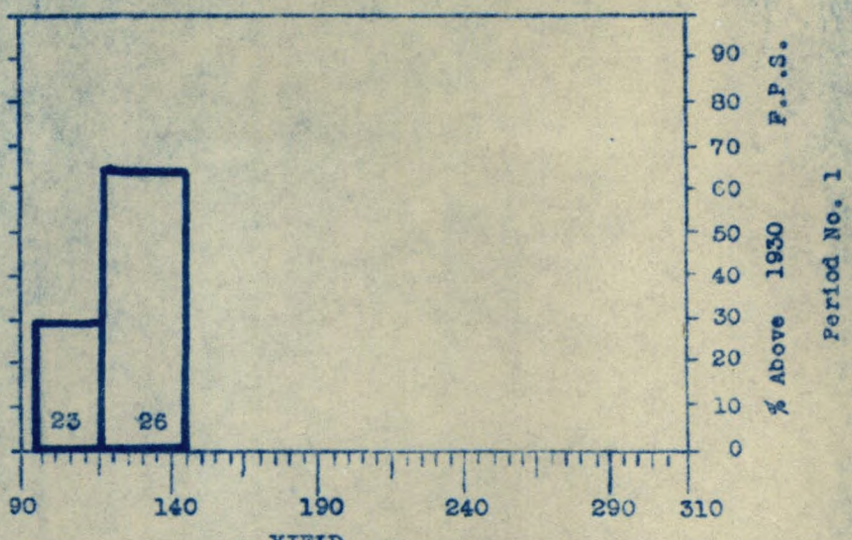


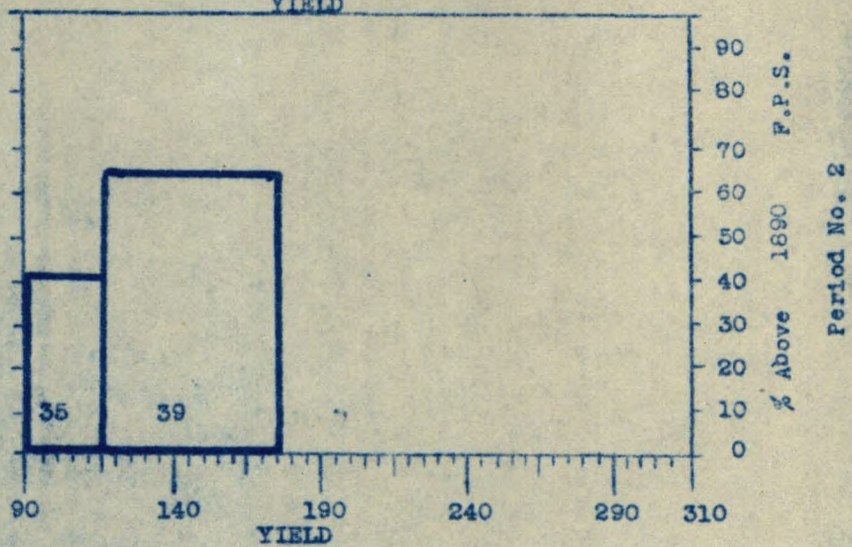


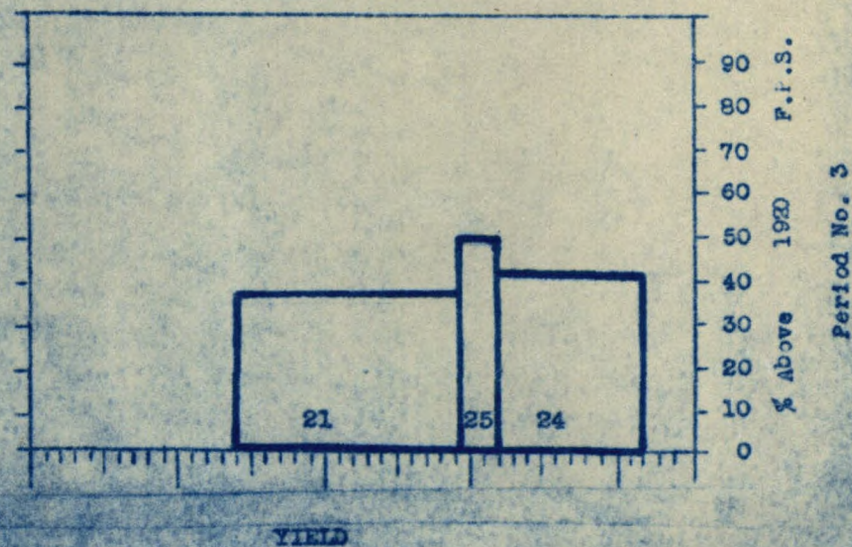


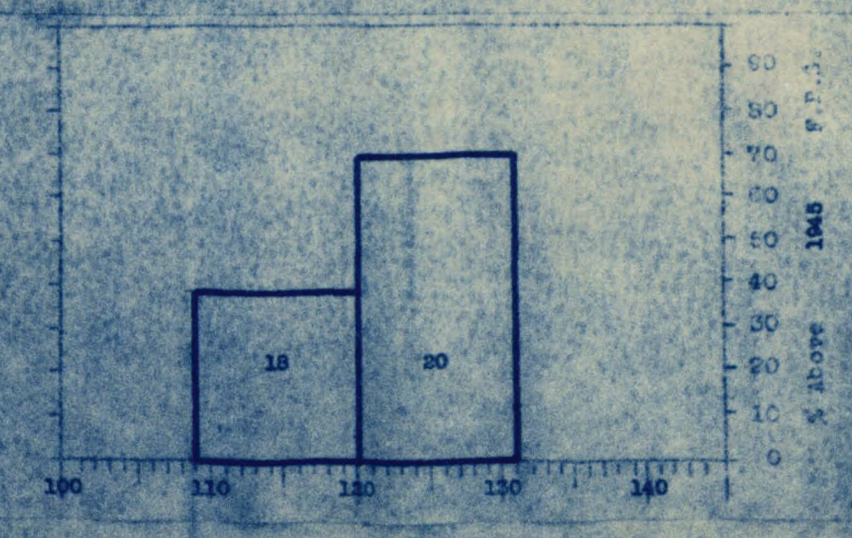


CORRELATION BETWEEN YIELD AND BALLISTIC LIMIT
HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
WIDTH " " " SPREAD OF RESULTS
NUMBER IN " " NO. OF RESULTS



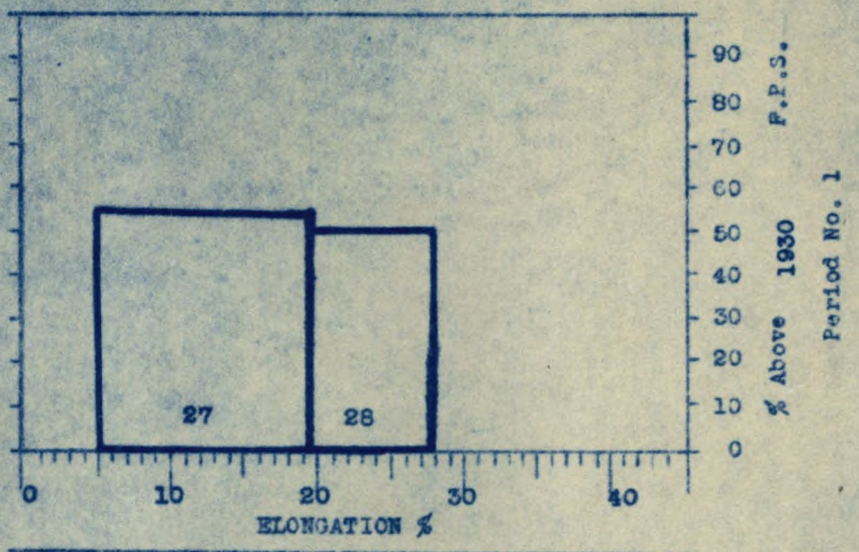


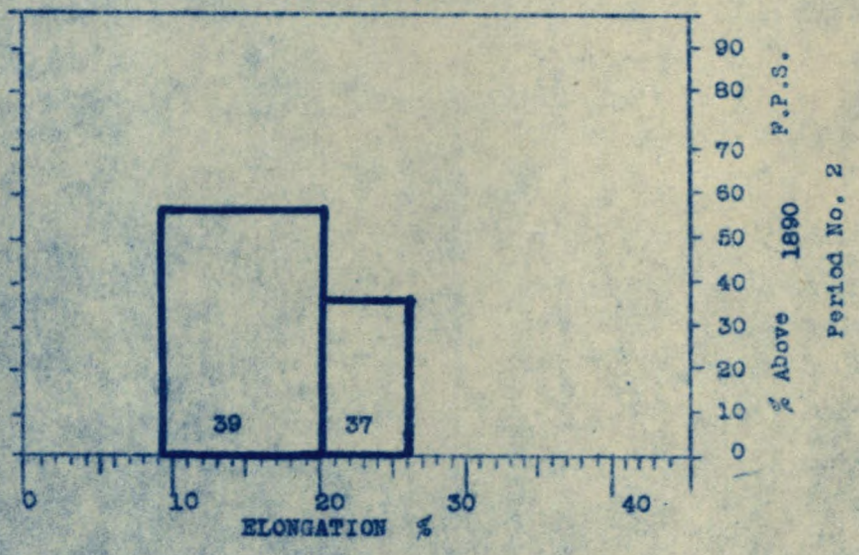


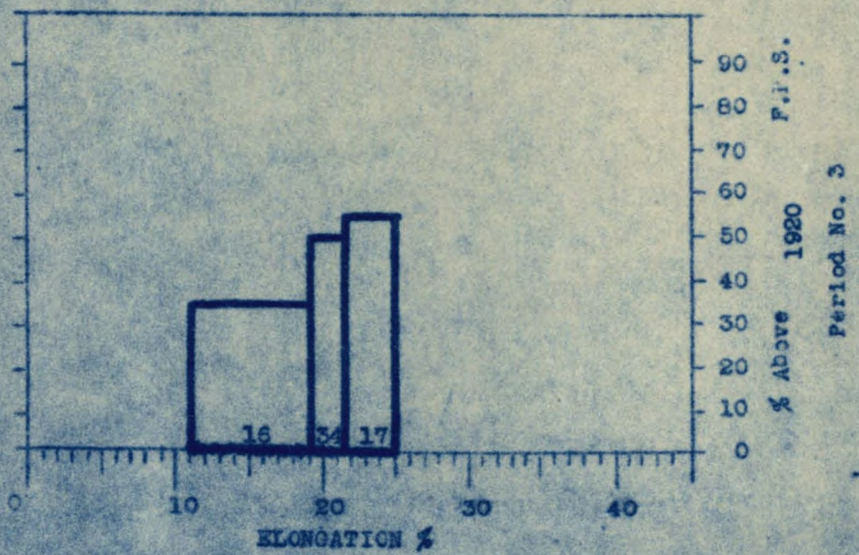


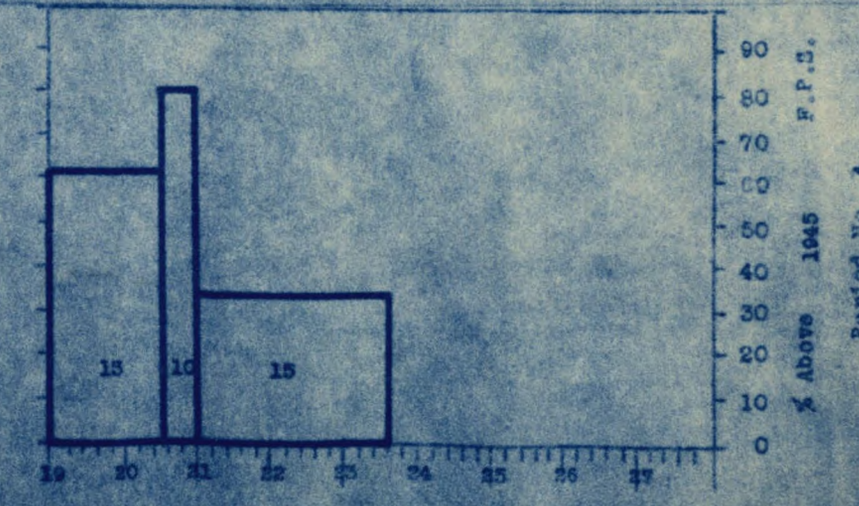
CORRELATION BETWEEN ELONG. AND BALLISTIC LIMIT

HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
WIDTH " " " SPREAD OF RESULTS
NUMBER IN " " NO. OF RESULTS

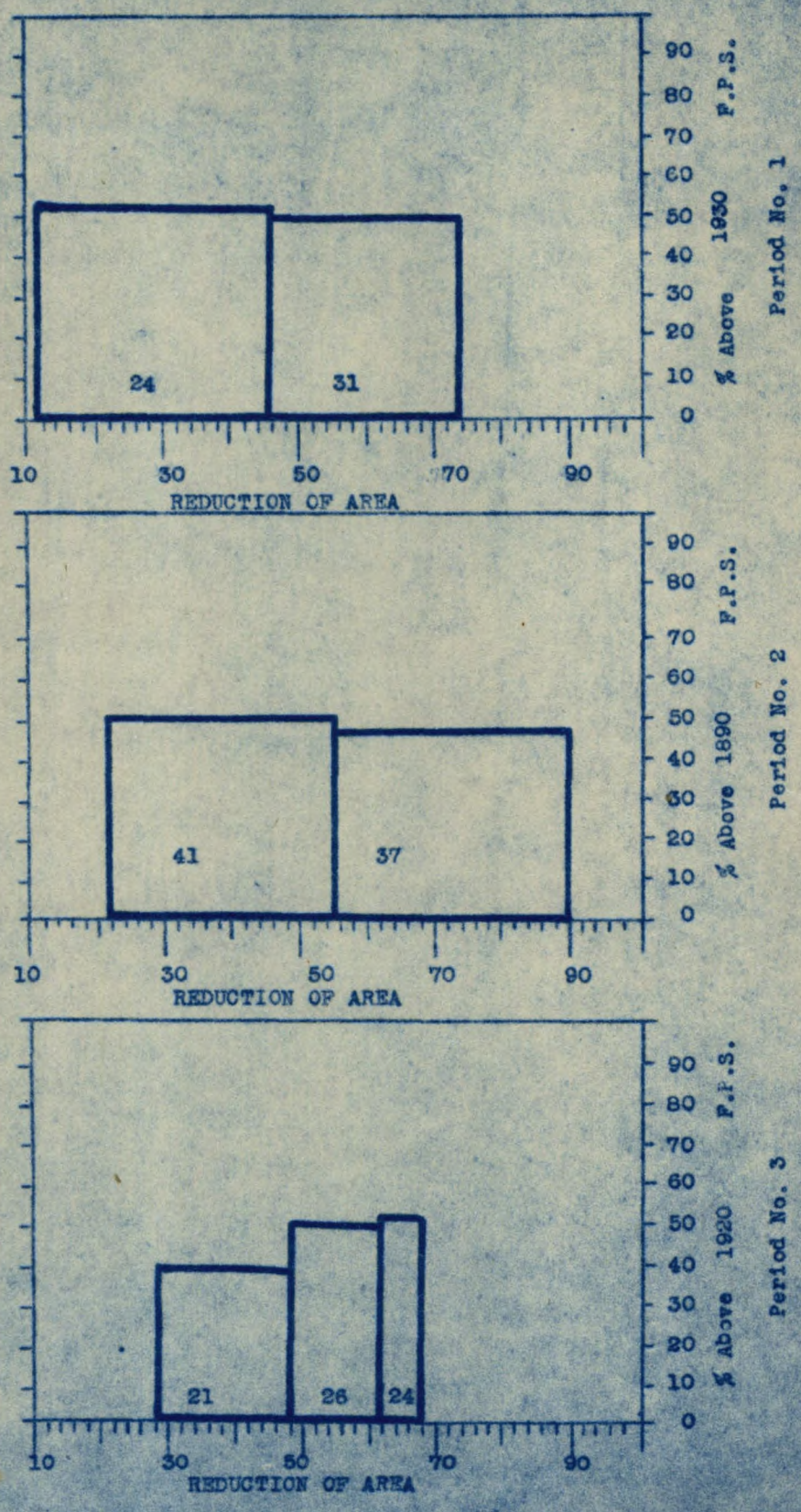


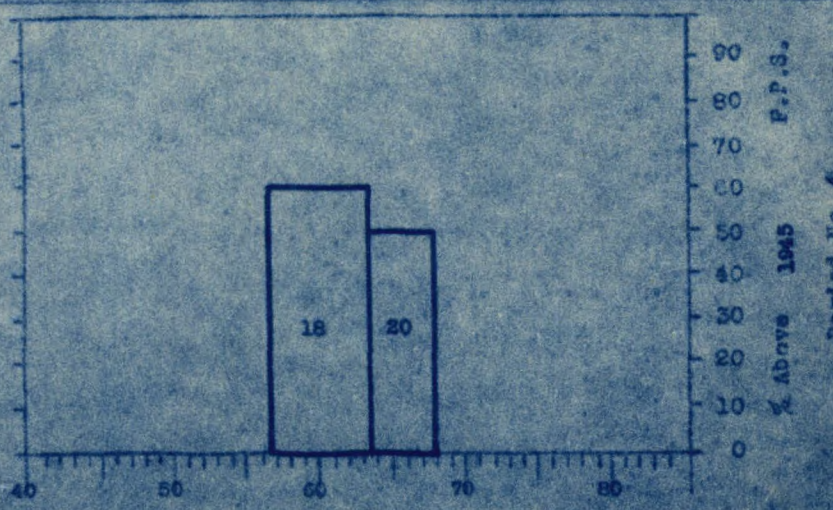


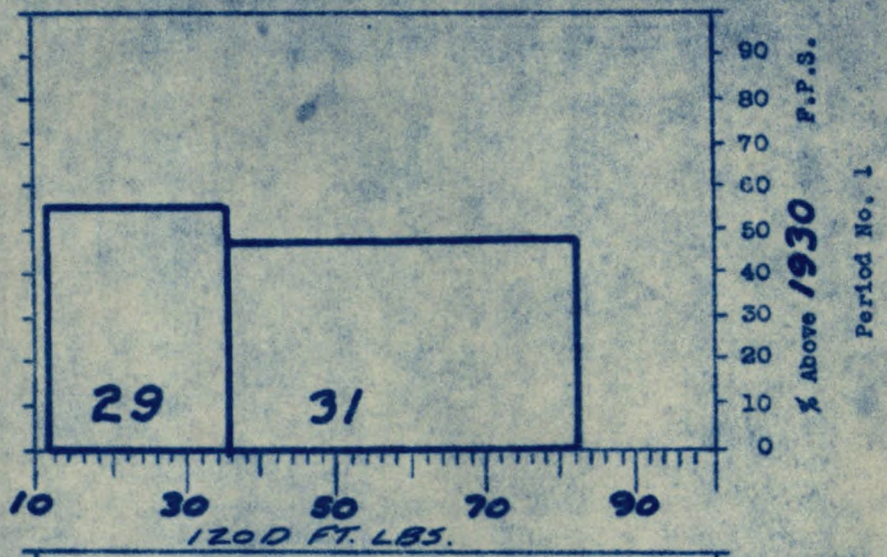
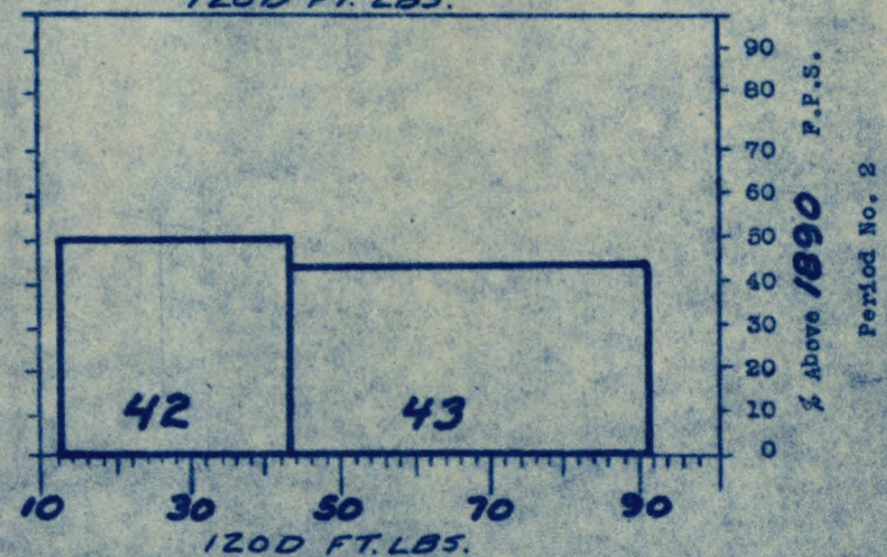
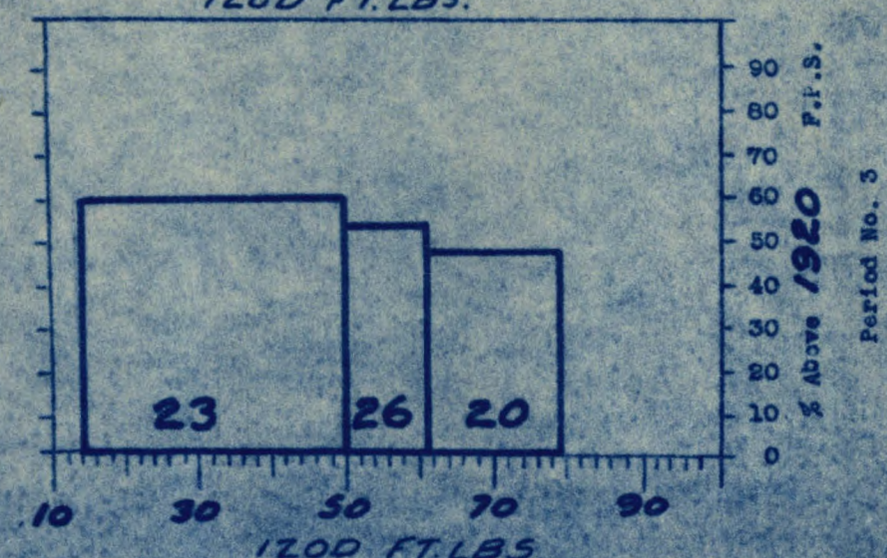
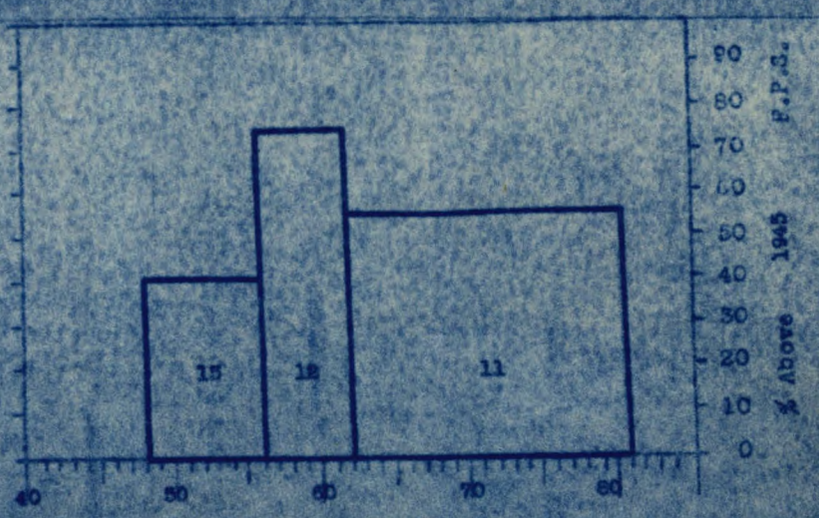




CORRELATION BETWEEN R.A. AND BALLISTIC LIMIT
HEIGHT OF BLOCK INDICATES ARMOUR QUALITY
WIDTH " " " SPREAD OF RESULTS
NUMBER IN " " NO. OF RESULTS





CORRELATION BETWEEN **1200** AND BALLISTIC LIMIT

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NUMBER IN " " NO. OF RESULTS