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OTTAWA January 9th, 1942.

# REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1144.

Armour Plate Improvement As Related To
Statistical Analysis of Manufacturing Data.

(Copy No. 53.)

BUREAU OF MINES
DIVISION OF METALLIC MINERALS

ORE DRESSING AND
METALLURGICAL LABORATORIES

CANADA
DEPARTMENT
OF
MINES AND RESOURCES
MINES AND GEOLOGY BRANCH

OTTAWA January 9th, 1942.

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### Armour Improvement:

Research may develop new analysis and manufacturing methods which will result in a superior quality of armour plate. Actual manufacturing records, however, give research data in mass production quantities. The information derived from this source is likely to be of much more immediate practical value than single laboratory experiments.

One might think that statistical analysis can only lead to relatively small improvements in armour plate and that radical departures from present methods of production must be made if great improvement in armour is to be expected. This is not necessarily so, however, for while the application of information obtained by statistical methods should lead gradually to ideal properties for armour plate, the tendencies or trends revealed by statistical methods would serve to intelligently direct experimental work designed to produce a markedly superior armour.

In order to show the possibilities of statistical analysis, a set of records was obtained from the General Steel Company. Page 2 shows the form in which the data were recorded:

DATE: Mar. 22 1941

THICK: 3 3/16 "; Cr ........; Ni ........; Mo ........; V ........

SOURCE: General Steel #84 Heat No.: #2BB..... Hardness: ........

## BALLISTICS

| Projectile | Velocity | Effect |
| --- | --- | --- |
| .37 mm. A.P. M 51 | 2005 | Partial Penetration |
| | 2045 | Complete Penetration |

Ballistic Limit: Velocity 2025 Feet per Second

## MECHANICAL

Yield: 117.500 p.s.i.
Ult. str.: 143.0 p.s.i.
Elongation, 2 in.: 4 %
Izod: 48.0 ft. lb.
B. H. N.: 270
"n" value: ..............
Reduction of Area 35.4%.

## MICROSTRUCTURE

Oxide rating: ..........
Slag rating: ..........
Grain size: ..........
Ferrite: ..........
Carbides: ..........
Class of structure:

## ANALYSIS

| | |
| --- | --- |
| C | 0.30 |
| Si | 0.30 |
| Mn | 0.50 |
| S | 0.012 |
| P | 0.025 |
| Ni | 2.53 |
| Cr | 0.50 |
| Mo | |
| V | |

## HARDENABILITY

Diam. of test piece: ..........
Rockwell "C":-
At base: ........
At ½ in.: ........
At 1 in.: ........
At 2 in.: ........

## THERMAL DATA

Poured ..........
Soaked ..........
Cogged ..........
Rolled ..........
Hardened ..........
Quench medium: ..........
Drawn ..........
Homogenized ..........

RATE OF COOLING THROUGH 1300° Fahr. -

After pouring: ..........
" cogging: ..........
" rolling: ..........
" hardening: ..........
" drawing: ..........
" homogenizing: ..........

## FURNACE DATA

Type of furnace: ..........

Size of melt: ..........tons; Time to melt: ..........hours..........mins.

Time from melt to pour: .......... hours ..........mins.

1st Slag: ..........; Time: ........; Analysis: C....Mn....Si....

2nd Slag: ..........; Time: ........; Analysis: C....Mn....Si....

3rd Slag: ..........; Time: ........; Analysis: C....Mn....Si....

Furnace additions: ..........ore; ..........lime; ..........

Ladle additions: ..........

## CASTING DATA

Type of Pouring Basin: ..........; Type of Ingot: ..........

Time to Pour: .......... secs. Time to Strip / Shake Out: ..........

REMARKS:

Ottawa, Canada.
October, 1941.
HHF:PES.

Armour Statistics Data Sheet No. 1.

Data Sheets:

The data were transferred to forms as shown on Page 2, so that information on every heat was available for plotting. Several methods of analyzing the data were proposed. These will be described in the following sections:

(1) Graphic presentation.

(2) Correlation factor.

(3) Ratio difference.

(4) Quality control.

Graphic Presentation:

Figures 1, 2, and 3 show the data plotted with Brinell hardness as a base. Some trends are evident. For example, it would appear that as hardness increases from 260 to 270, ballistic limits increase, reduction of area, impact and elongation decrease. However, the scattered nature of the data indicates that every property must be considered as a distribution within a range.

In order to see what relationship exists between the variables (for example, Brinell hardness and ballistic limit) the correlation coefficient can be obtained.

Calculation of Correlation Coefficient:

"Correlation implies commonness of causation with respect to two or more phenomena. This does not necessarily mean a relationship of cause and effect." (Engineer's Manual of Statistical Methods, L. Simon). For example, silicon may correlate with ballistic limit but this does not necessarily mean that silicon has any effect on ballistic limit. Perfect correlation is indicated by a correlation coefficient of 1.0; no relationship between phenomena is indicated by

(Continued on Page 6)

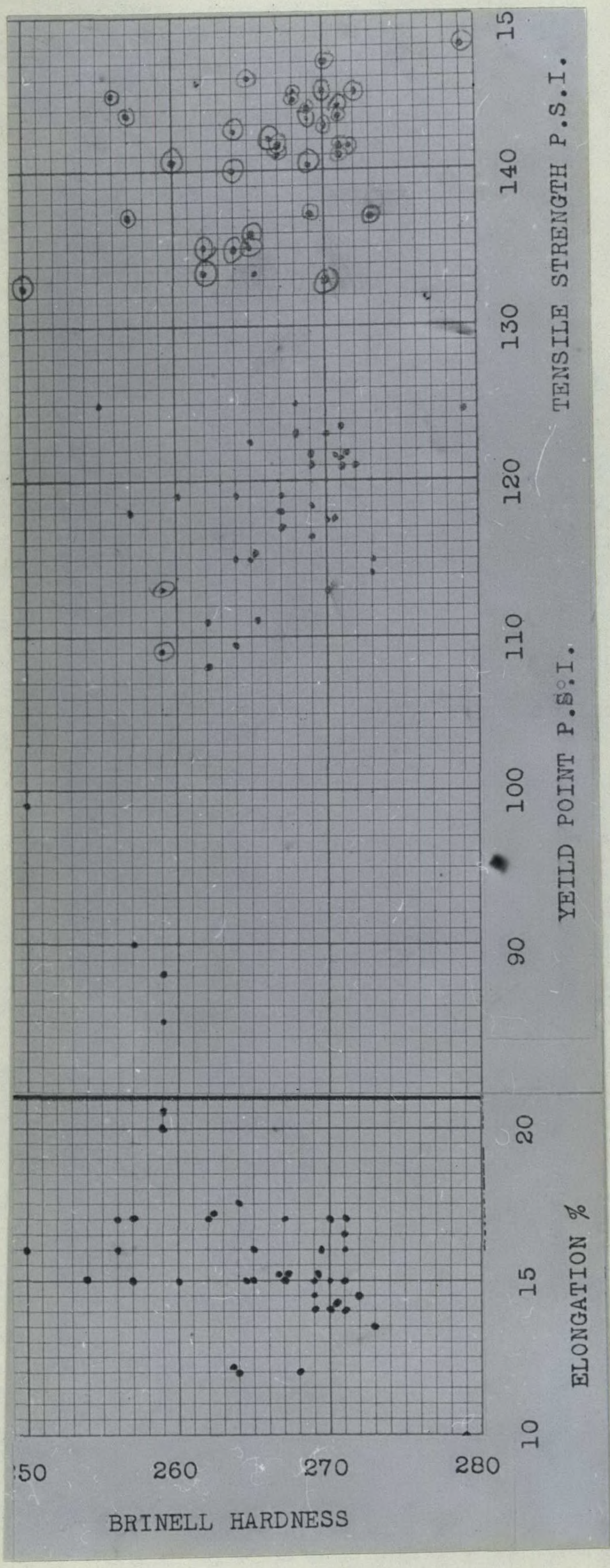



Figure 1.

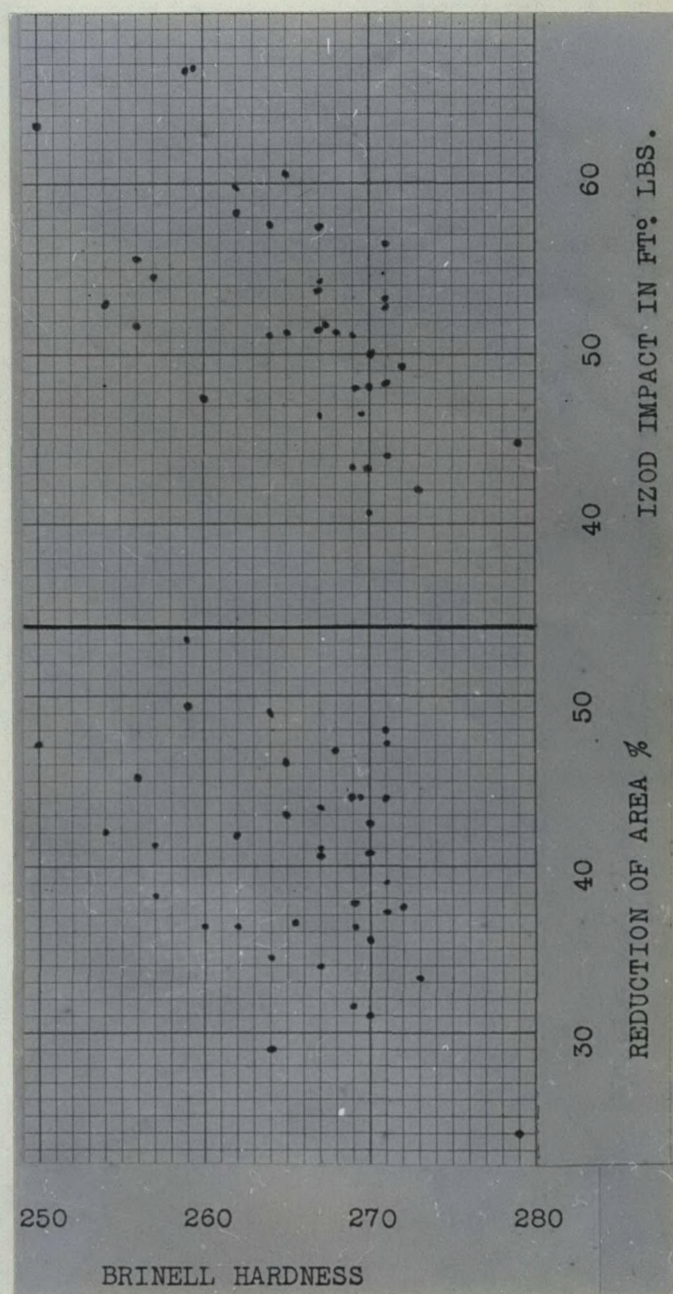



Figure 2.

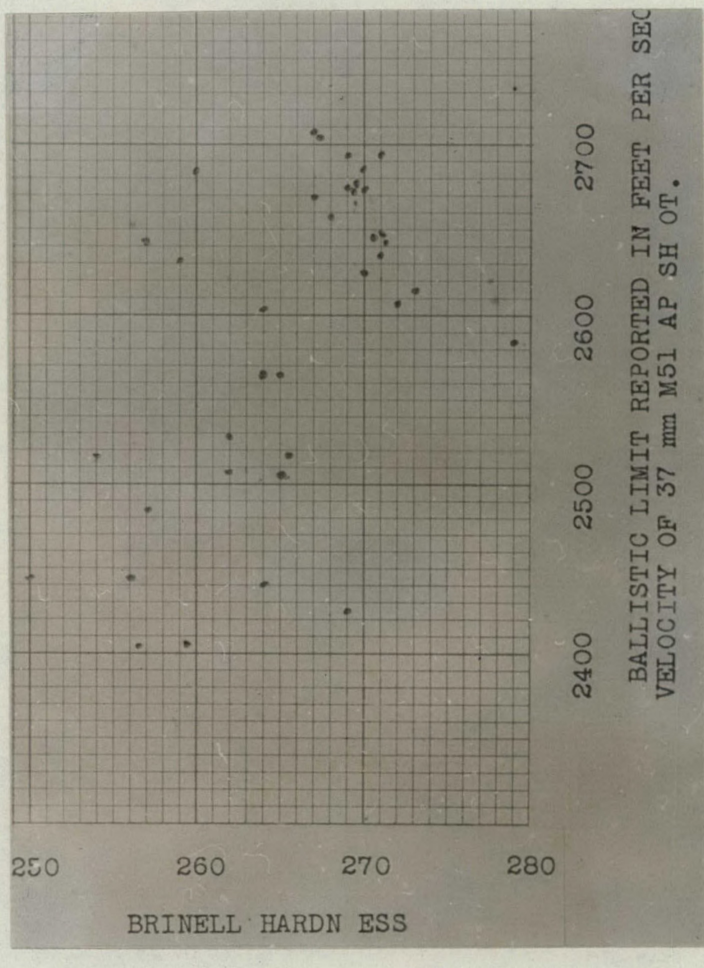

250 260 270 280
BRINELL HARDN ESS
2400 2500 2600 2700
BALLISTIC LIMIT REPORTED IN FEET PER SEC
VELOCITY OF 37 mm M51 AP SH OT.

Figure 3.

(Calculation of Correlation Coefficient, cont'd) -

a correlation coefficient of zero. In data subject to statistical variation perfect correlation is rarely obtained.

$$r = \frac{\Sigma(X - \bar{X})\ (Y - \bar{Y})}{\sqrt{\Sigma(X - \bar{X})^2\ \Sigma(Y - \bar{Y})^2}}$$

KEY:

| | | |
|---|---|---|
| $r$ | = | correlation coefficient |
| $\Sigma$ | = | the sum of |
| $X$ | = | a Brinell reading |
| $\bar{X}$ | = | average of the Brinell readings |
| $Y$ | = | a ballistic limit |
| $\bar{Y}$ | = | average of the ballistic limits |

Solving this equation using the data of Page 7 this becomes:

$$r = \frac{\Sigma(X - \bar{X})\ (Y - \bar{Y})}{\sqrt{(X - \bar{X})^2\ \Sigma(Y - \bar{Y})^2}}$$

$$= \frac{12,261}{\sqrt{1391 \times 312,224}}$$

$$\log r = 4.088525 - \tfrac{1}{2}(3.14333 + 5.49447)$$

$$\log r = \bar{1}.769625$$

$$r = 0.58833$$

$$r = 0.58 \text{ approx.}$$

This means that the correlation between the Brinell hardness and the ballistic limit is 0.58. This type of calculation is of value in determining the relative degree of relationship between, for example, Brinell and ballistic limit, yield point and ballistic limit, carbon per cent and ballistic limit, etc.

| X | Y | $X-\bar{X}$ | $Y-\bar{Y}$ | $(X-\bar{X})^2$ | $(Y-\bar{Y})^2$ | $(X-\bar{X})(Y-\bar{Y})$ |
|---|---|---|---|---|---|---|
| 279 | 2585 | +14 | -3 | 196 | 9 | -42 |
| 273 | 2615 | +8 | +27 | 64 | 729 | +216 |
| 272 | 2605 | +7 | +17 | 49 | 289 | +119 |
| 271 | 2695 | +6 | +107 | 36 | 11,449 | +642 |
| 271 | 2635 | +6 | +47 | 36 | 1,929 | 282 |
| 271 | 2645 | +6 | +57 | 36 | 3,249 | 342 |
| 271 | 2645 | +6 | +57 | 36 | 3,249 | 342 |
| 270 | 2625 | +5 | +37 | 25 | 1,369 | 185 |
| 270 | 2675 | +5 | +87 | 25 | 7,569 | 435 |
| 270 | 2685 | +5 | +97 | 25 | 9,409 | 485 |
| 269 | 2695 | +4 | +107 | 16 | 11,449 | 428 |
| 269 | 2675 | +4 | +87 | 16 | 7,569 | 348 |
| 269 | 2675 | +4 | +87 | 16 | 7,569 | 348 |
| 269 | 2675 | +4 | +87 | 16 | 7,569 | 348 |
| 269 | 2425 | +4 | -163 | 16 | 26,569 | -652 |
| 268 | 2655 | +3 | +67 | 9 | 4,489 | +201 |
| 267 | 2670 | +2 | +82 | 4 | 6,724 | +164 |
| 267 | 2705 | +2 | +117 | 4 | 13,689 | +234 |
| 267 | 2705 | +2 | +117 | 4 | 13,689 | +234 |
| 265 | 2505 | 0 | -77 | 0 | 5,929 | 0 |
| 265 | 2515 | 0 | -73 | 0 | 5,329 | 0 |
| 265 | 2565 | 0 | -23 | 0 | 529 | 0 |
| 264 | 2605 | -1 | +17 | 1 | 289 | -17 |
| 264 | 2565 | -1 | -23 | 1 | 529 | +23 |
| 264 | 2440 | -1 | -148 | 1 | 21,904 | +148 |
| 262 | 2505 | -3 | -83 | 9 | 6,889 | +249 |
| 262 | 2525 | -3 | -63 | 9 | 3,969 | +189 |
| 260 | 2685 | -5 | +3 | 25 | 9 | -15 |
| 259.5 | 2405 | -5.5 | -183 | 30 | 33,489 | +1,006 |
| 259 | 2630 | -6 | +42 | 36 | 1,764 | -252 |
| 257 | 2640 | -8 | +52 | 64 | 2,704 | -416 |
| 257 | 2485 | -8 | -103 | 64 | 10,609 | +824 |
| 256.5 | 2405 | -8.5 | -183 | 72 | 33,489 | +1,555 |
| 256 | 2445 | -9 | -143 | 81 | 20,449 | +1,287 |
| 253 | 2515 | -12 | -73 | 144 | 5,329 | +876 |
| 250 | 2445 | -15 | -143 | 225 | 20,449 | +2145 |
| $\Sigma X$ = 9551 | $\Sigma Y$ = 93165 | | | 1391 | 312,224 | 12,261 |
| r=36 | r=36 | | | | | |
| $\bar{X}$ = 265.3 | $\bar{Y}$ = 2587.9 | | | | | |
| 265 | 2588 | | | | | |

Ratio Difference:

As the number of results increases, the calculation of the correlation coefficient becomes more and more laborious. It is desirable to know not only whether or not a property is correlated to ballistic limit, but also in what range of the property, if any, are the best ballistic limits likely to occur. This information can be derived by the use of the fairly simple ratio difference technique. Consider Figure 4, in which the data of Figure 3 have been divided approximately in half. (The term median should be substituted for average). The information expressed in ratio form is as follows:

| Ballistic Limit Ranges | | Frequency of Results |
|---|---|---|
| 2600 - 2705 | 7 | 16 |
| 2405 - 2590 | 13 | 2 |
| Brinell Ranges | 250-267 | 268-279 |

In the Brinell range 250-267, 7/20 = 0.35 per cent are above 2600 F.S. Ballistic Limit.

In the Brinell range 268-279, 16/18 =0.89 per cent are above 2600 F.S. Ballistic Limit.

The question immediately arises, "To what extent might the above difference in ratios be due to chance?" This can be answered by using the chart shown in Figure 5, derived from "An Engineer's Manual of Statistical Methods," by Major L. Simon. This chart is approximately true only for samples from a lot known to be 50 per cent good and 50 per cent bad. By using the medians, this requirement is met. By applying this chart to the ratios 7/20, 16/18, the following results are obtained:

(Ratio Difference, cont'd) -

Ratio difference, 0.89-0.35 = 0.54

Number effect = 1/20 + 1/18 = 0.1055

Probability of chance producing
this ratio difference (from
chart) = 0.15/100 = 15/10,000

Significance = 99.85 per cent = 9985/10,000.

With the ratio difference method it is possible to find the relation between two different properties and also the significance of this relationship. The following pages will show this method applied to show the relationship between chemical and physical properties and ballistic limits:

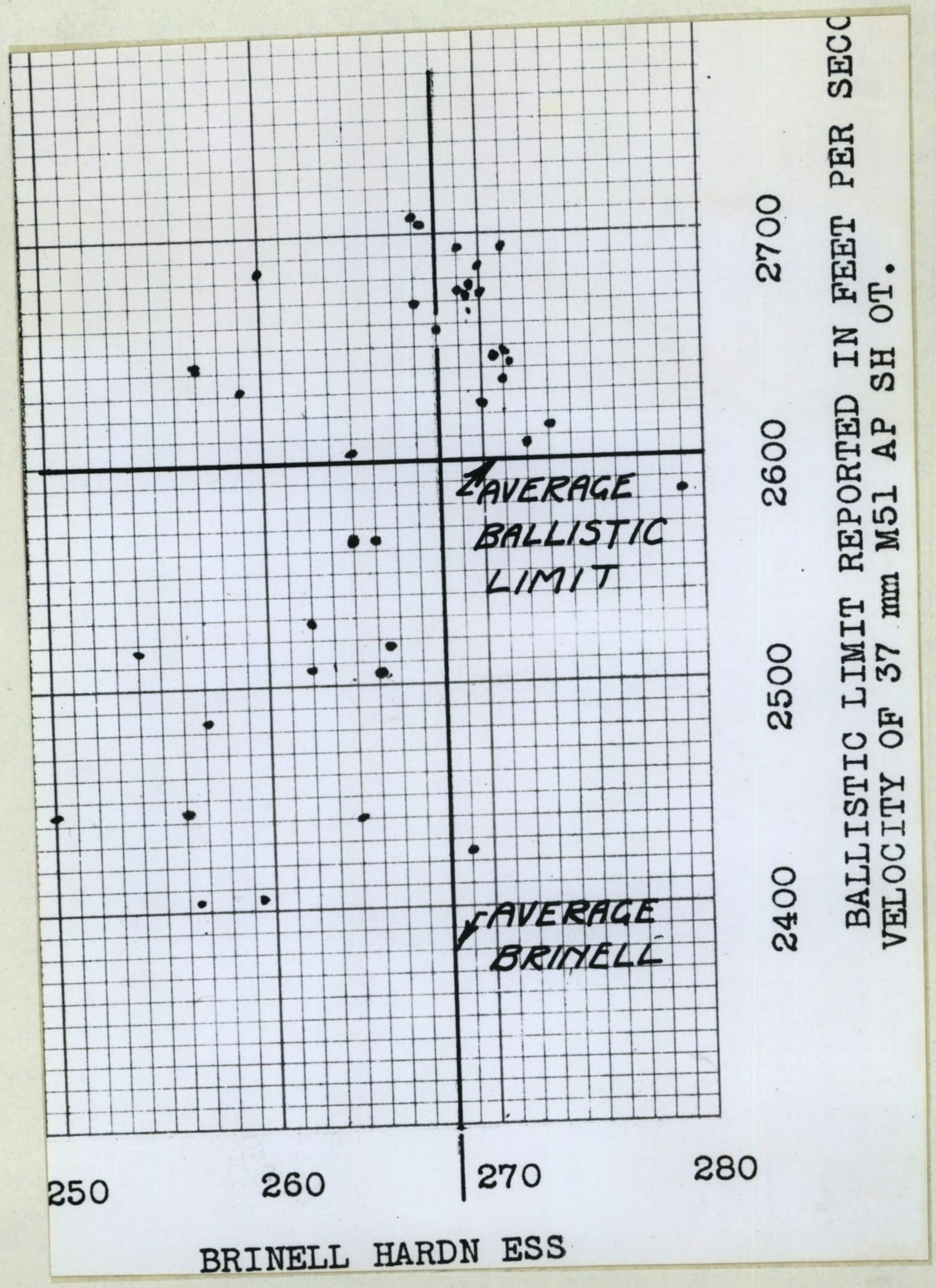



Figure 4. -- Ratio Difference.

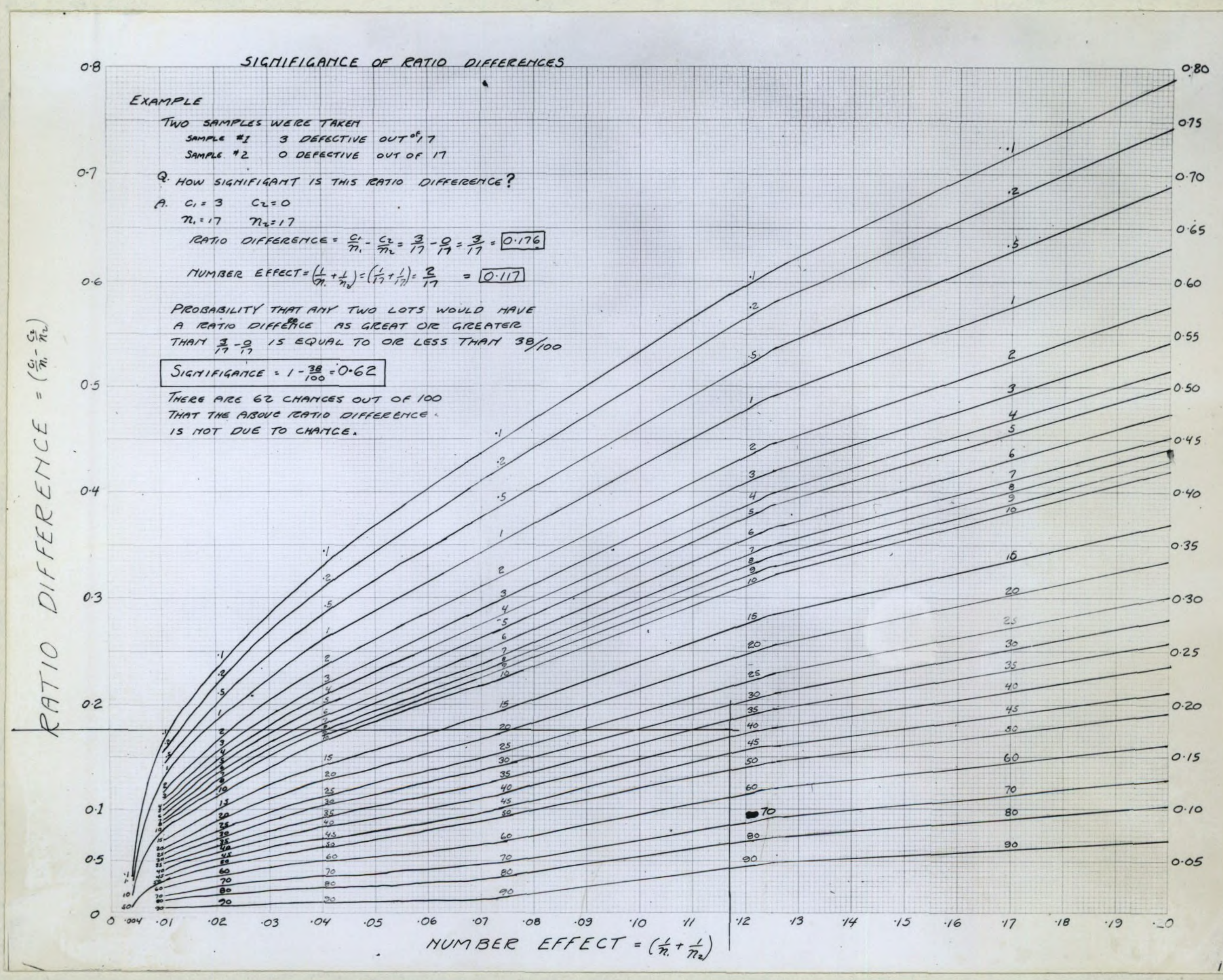



Figure 5. -- Significance.

Significance: (Explanation for Figure 5, Page 11)

Major Leslie E. Simon, in "Engineer's Manual of Statistical Methods," gives the following methods for obtaining the significance of ratio differences:

(a)

$$t = \frac{(x/n) - (1/2n)}{\sqrt{2}\sqrt{PQ/n}}$$ for small samples of equal size.

(b)

$$t = \frac{(c_1/n_1) - (c_2/n_2)}{\sqrt{PQ(1/n_1 + 1/n_2)}}$$ for large samples of the order of 50.

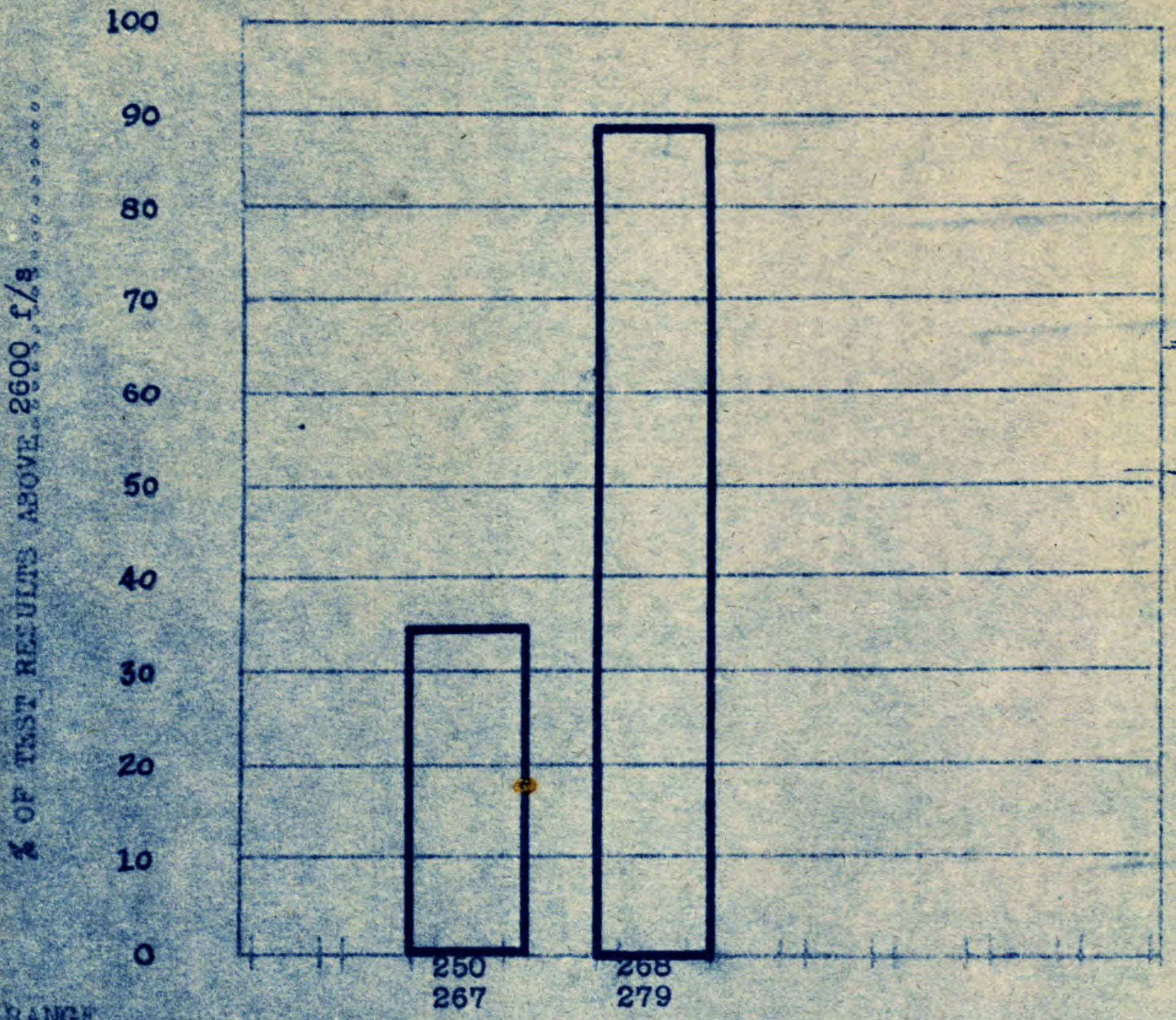
NOTE:

- $t$ = number of standard deviations (above and below the average) within which ratio differences equal to or less than $(\frac{x}{n})$ or $(\frac{c1}{n_1} - \frac{c2}{n_2})$ would fall due to chance.
- $x/n$ = ratio difference.
- $n$ = number of samples.
- $c_1$ = number effective in Sample $n_1$.
- $c_2$ = number effective in Sample $n_2$.
- $P$ = proportion effective.
- $Q$ = proportion defective.

Since the manner of selecting data always arranges P and Q = 0.5, these factors are constants. For the purpose of this investigation we are not so much concerned with the actual significance as with the relative degree of significance. For those interested in actual degree of significance we would suggest that they consult Major Simon's text. The chart of Page 11 was constructed using Equation (a) up to 0.07 number effect and Equation (b) from 0.12 to 0.20 number effect.

CORRELATION BETWEEN Brinell ...... & Ballistic Limit

IN 3" Armour ..... FROM General ........




| RANGE | | |
|---|---|---|
| No. above 2600 f/s: | 7 | 16 |
| Total number of test results: | 20 | 18 |
| Percentage above: | 35 | 89 |
| Ratio difference: | 54 | |
| Number effect: | .05 + 0.0555= .1055 | |

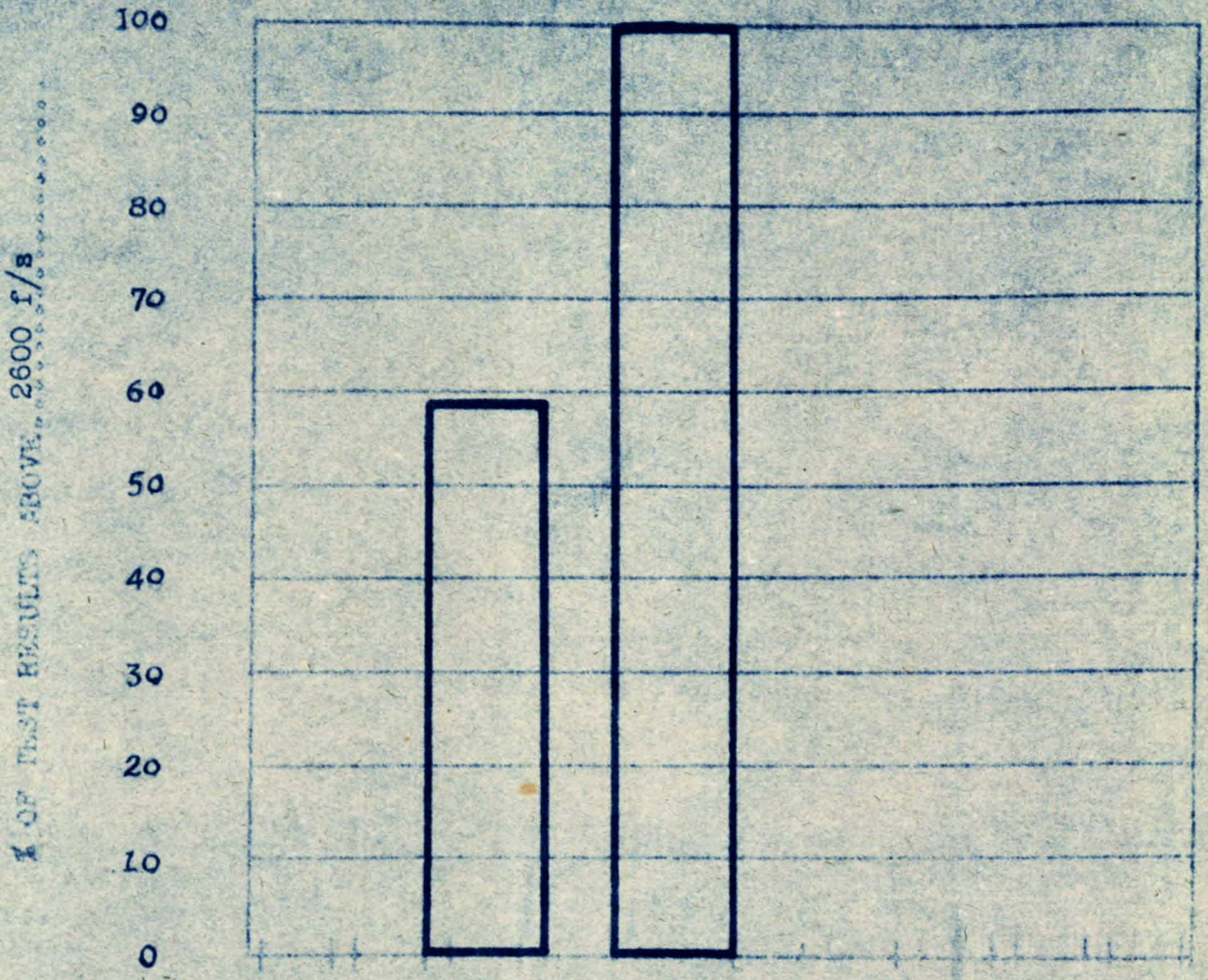
Significance:* 99.85 ..... %.

*(NOTE: This means that (100-99.85) equals the percentage of the time the above ratio difference would occur due to chance.)

Armour Statistics
Data Sheet No. 5.

CORRELATION BETWEEN **Carbon** ........ & **Ballistic Limit** ...

IN. . **3" Armour** . . . . FROM. **General** . . . . . .




| | | |
|---|---|---|
| RANGE | .26<br>.29 | .30<br>.35 |
| No. above 2600 f/s: | 13 | 20 |
| Total number of test results: | 22 | 20 |
| Percentage above: | .59 | 100 |

Ratio difference: ............ .41 ............

Number effect: ............ .095 ............

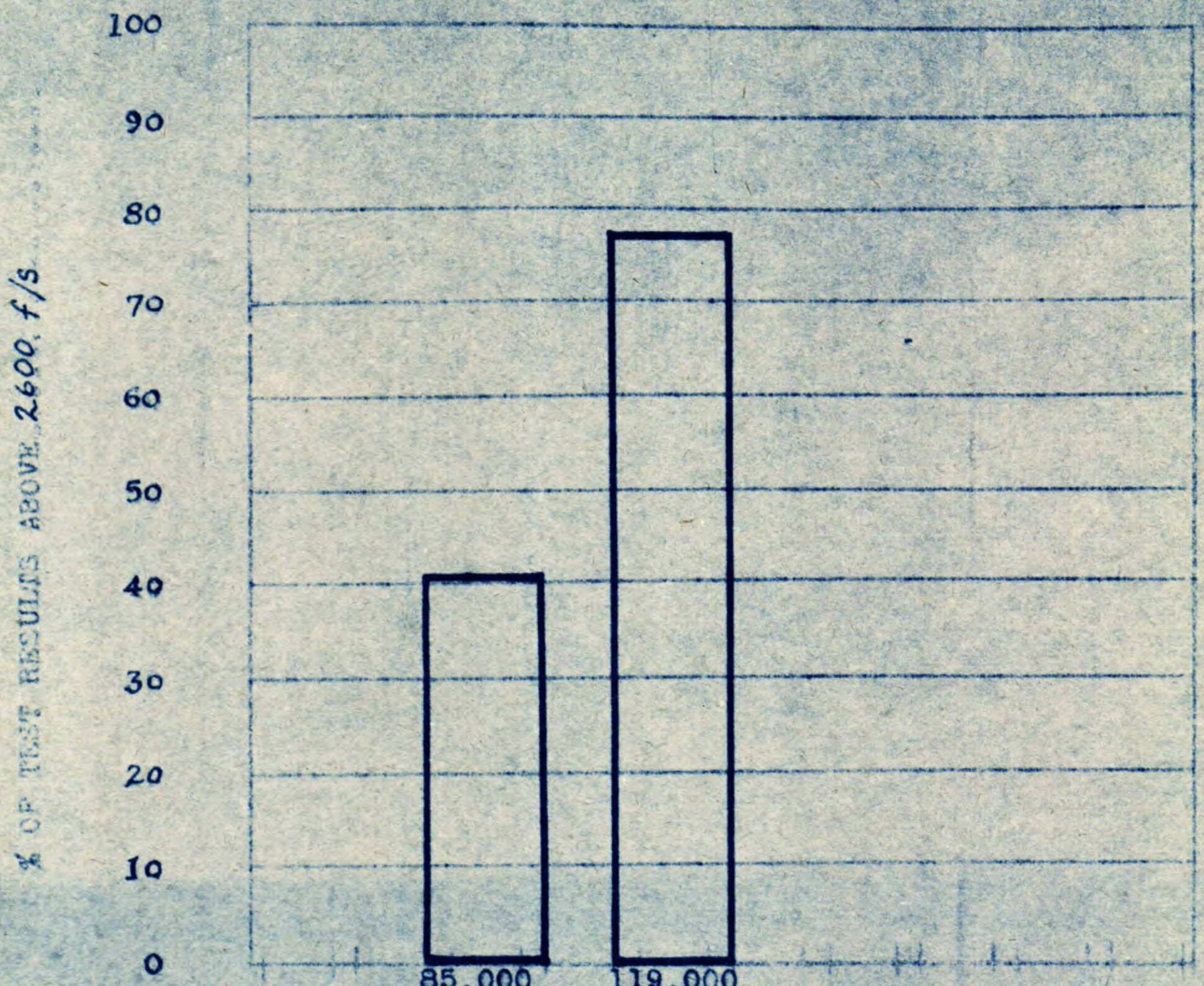
Significance:* .... 99 ..... %.

*(NOTE: This means that (100-99 %) equals the percentage of the time the above ratio difference would occur due to chance.)

Armour Ballistics
[illegible] Sheet No. 6.

CORRELATION BETWEEN ..Yield.......&...Ballistic Limit

IN..3" Armour..... FROM..General.......




| | | |
|---|---|---|
| RANGE | 85,000<br>118,900 | 119,000<br>133,500 |
| No. above 2600 f/s: | 7 | 17 |
| Total number of test results: | 17 | 22 |
| Percentage above: | .41 1 | .77 2 |

Ratio difference: .361

Number effect: .0588 ± .0454 = .1042

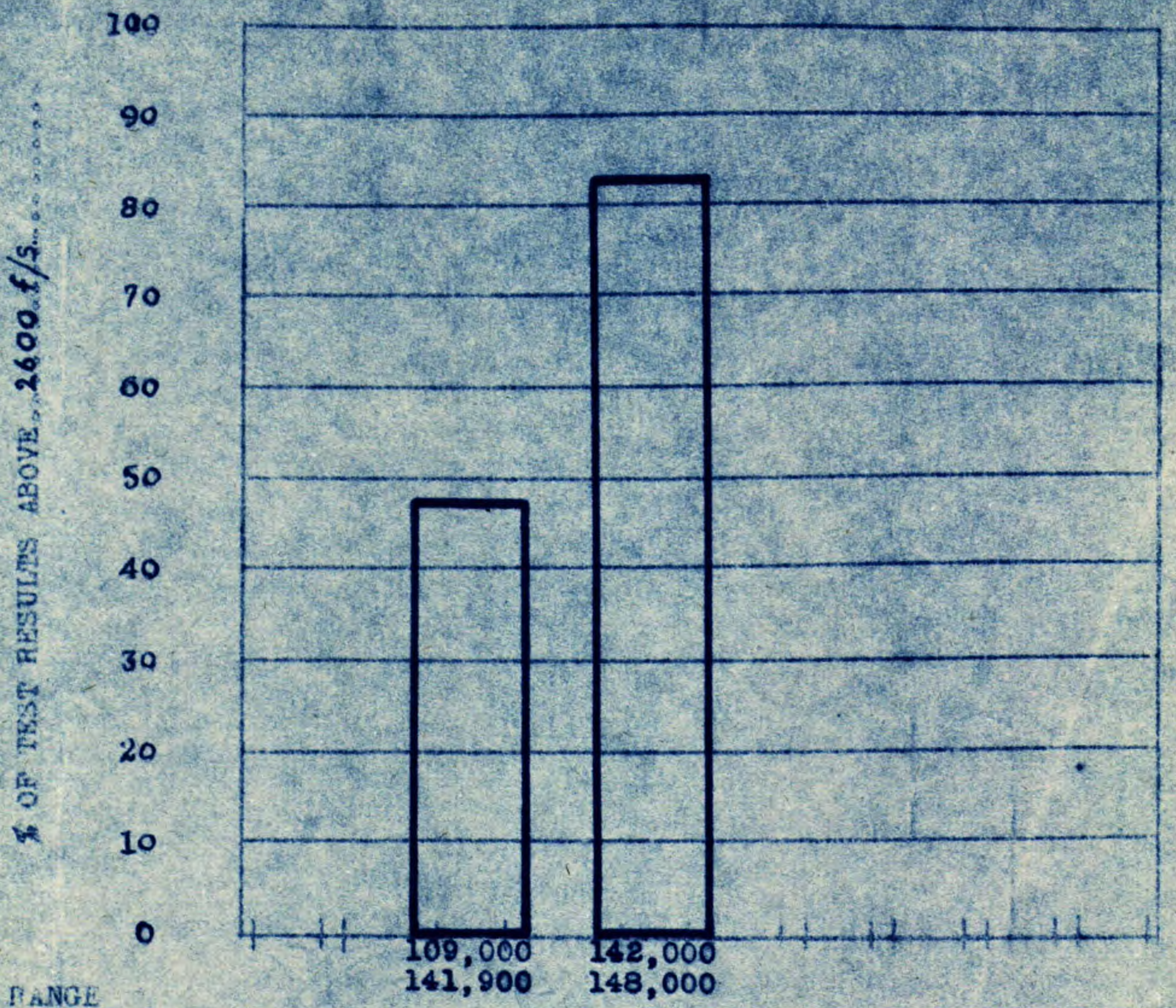
Significance:* ....96.5..%.

*(NOTE: This means that (100-96.5%) equals the percentage of the time the above ratio difference would occur due to chance.)

Armour Statistics
Data Sheet No. 5.

CORRELATION BETWEEN **Tensile Strength & Ballistic Limit**

IN **3" Cast Armour** FROM **General**




RANGE

| | | |
|---|---|---|
| No. above 2600 f/s: | 10 | 14 |
| Total number of test results: | 21 | 17 |
| Percentage above: | .47 6 | .82 3 |

Ratio difference: .347

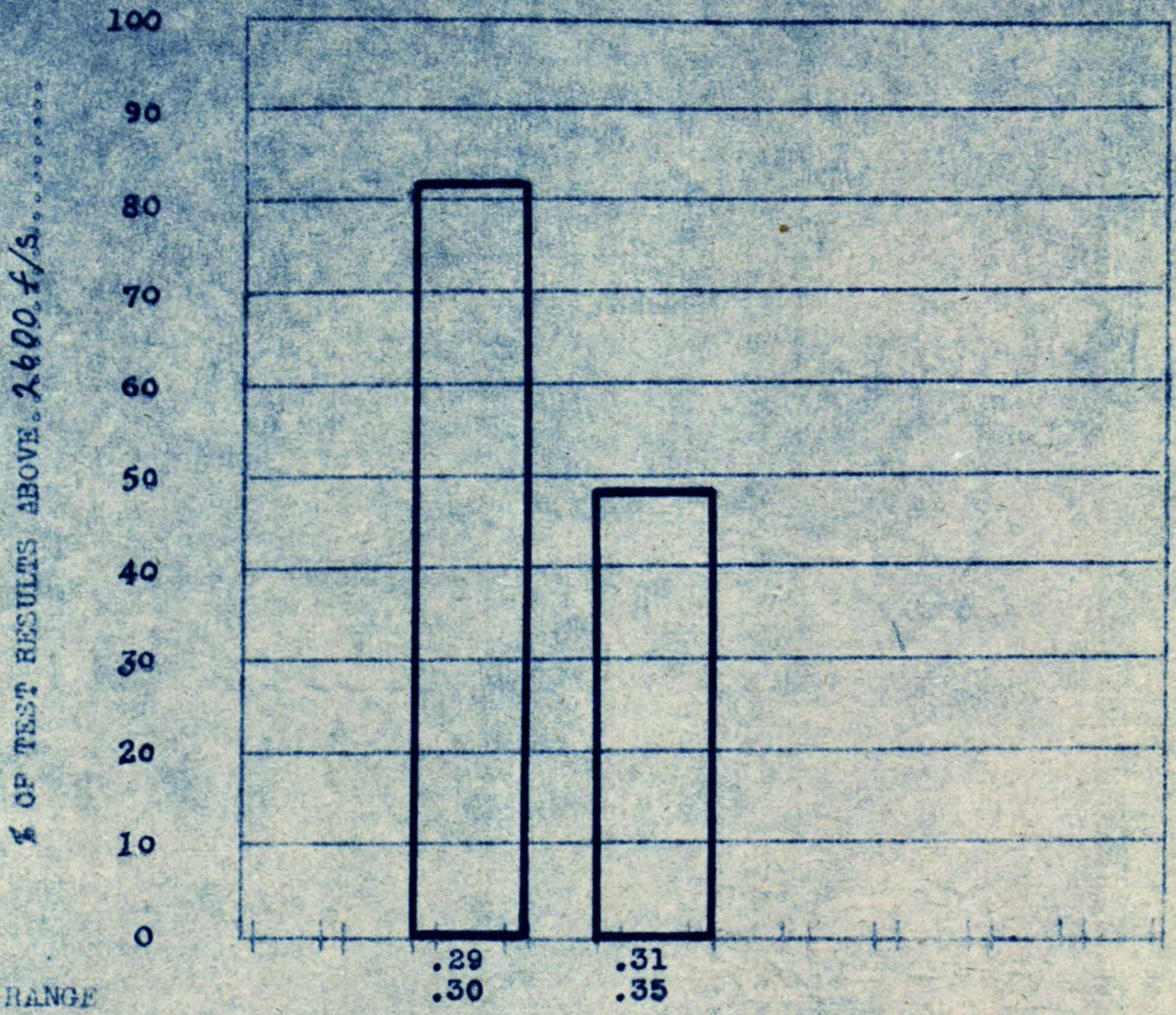
Number effect: .0476 plus .0589 - .1065

Significance:* 95 %.

*(NOTE: This means that (100-95 %) equals the percentage of the time the above ratio difference would occur due to chance.)

CORRELATION BETWEEN Silicon ........ & Ballistic Limit

IN. 3" Armour ........ FROM. General ........




| | | |
|---|---|---|
| RANGE | .29 – .30 | .31 – .35 |
| No. above 2600 f/s: | 13 | 11 |
| Total number of test results: | 16 | 23 |
| Percentage above: | .81 | .48 |

Ratio difference: .81 - .48 = .33

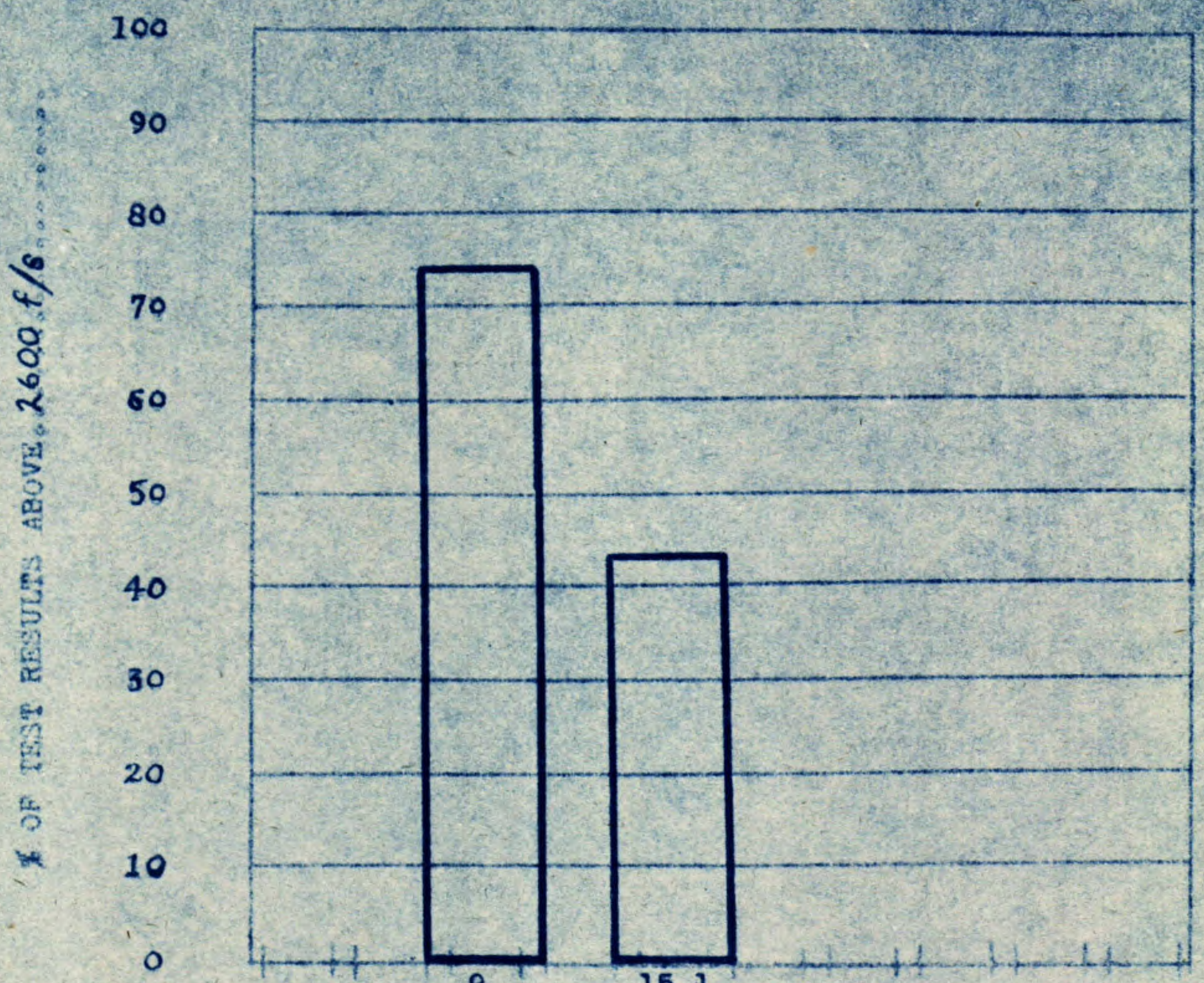
Number effect: .0625 plus .0434 = .1059

Significance:* 94 %.

*(NOTE: This means that (100-94%) equals the percentage of the time the above ratio difference would occur due to chance.)

CORRELATION BETWEEN Elongation ..... & . Ballistic Limit ..

IN. 3" Armour ..... FROM. General .....




| RANGE | 9<br>15 | 15.1<br>20.5 |
|---|---|---|
| No. above 2600 f/s: | 17 | 7 |
| Total number of test results: | 23 | 16 |
| Percentage above: | .74 | .43.7 |

Ratio difference: .303

Number effect: .0425 plus .0625 = .106

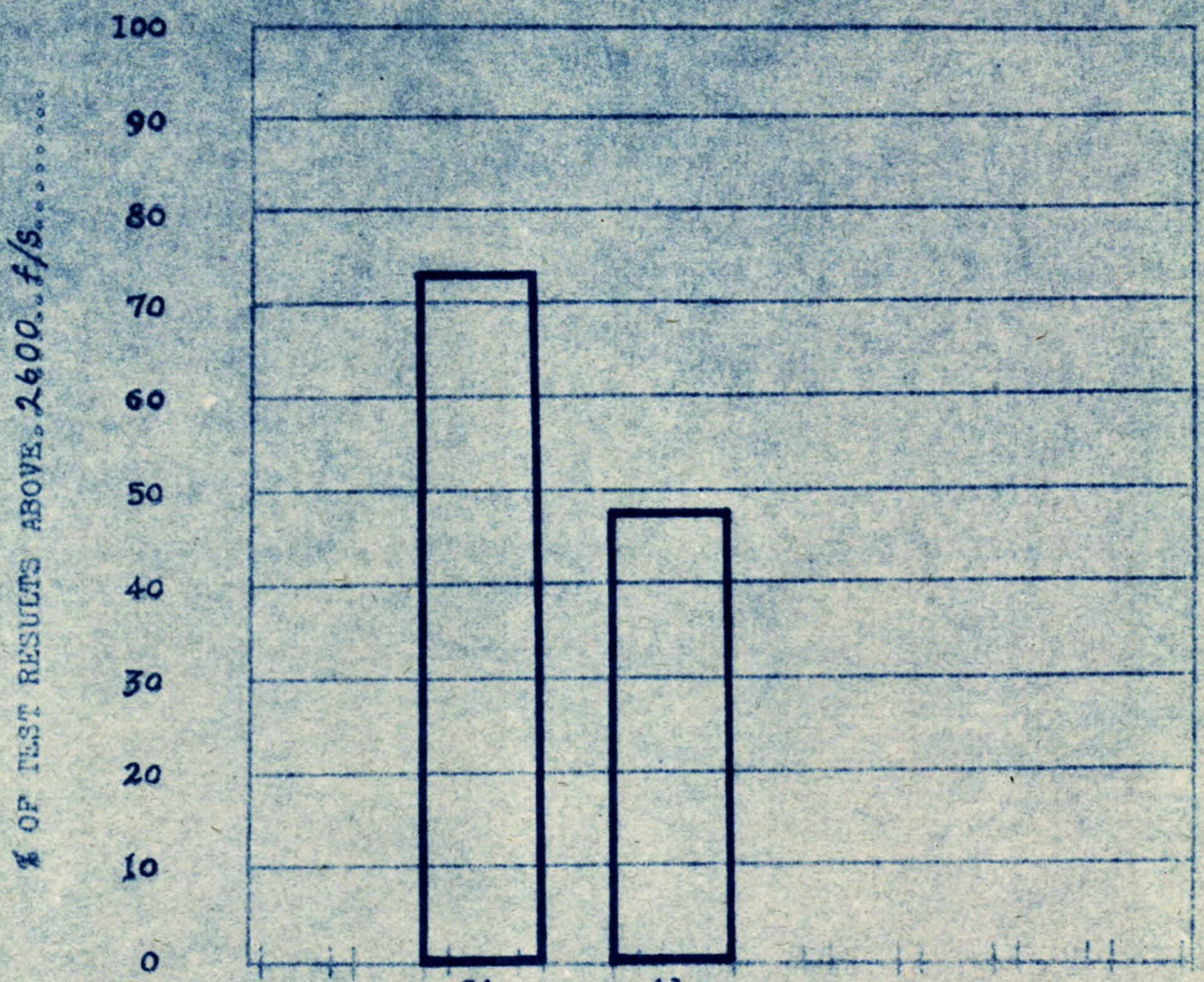
Significance:* 92 %.

*(NOTE: This means that (100-92 %) equals the percentage of the time the above ratio difference would occur due to chance.)

Armour Statistics
Data Sheet No. 5.

CORRELATION BETWEEN **Red. of Area . . & . . Ballistic Limit**

IN. **3" Armour** ...... FROM **General** ........




| | | |
|---|---|---|
| RANGE | 24<br>40 | 41<br>53 |
| No. above 2600 f/s: | 14 | 9 |
| Total number of test results: | 19 | 19 |
| Percentage above: | 73.8 | 47.4 |

Ratio difference: .......... 26.4 ..........

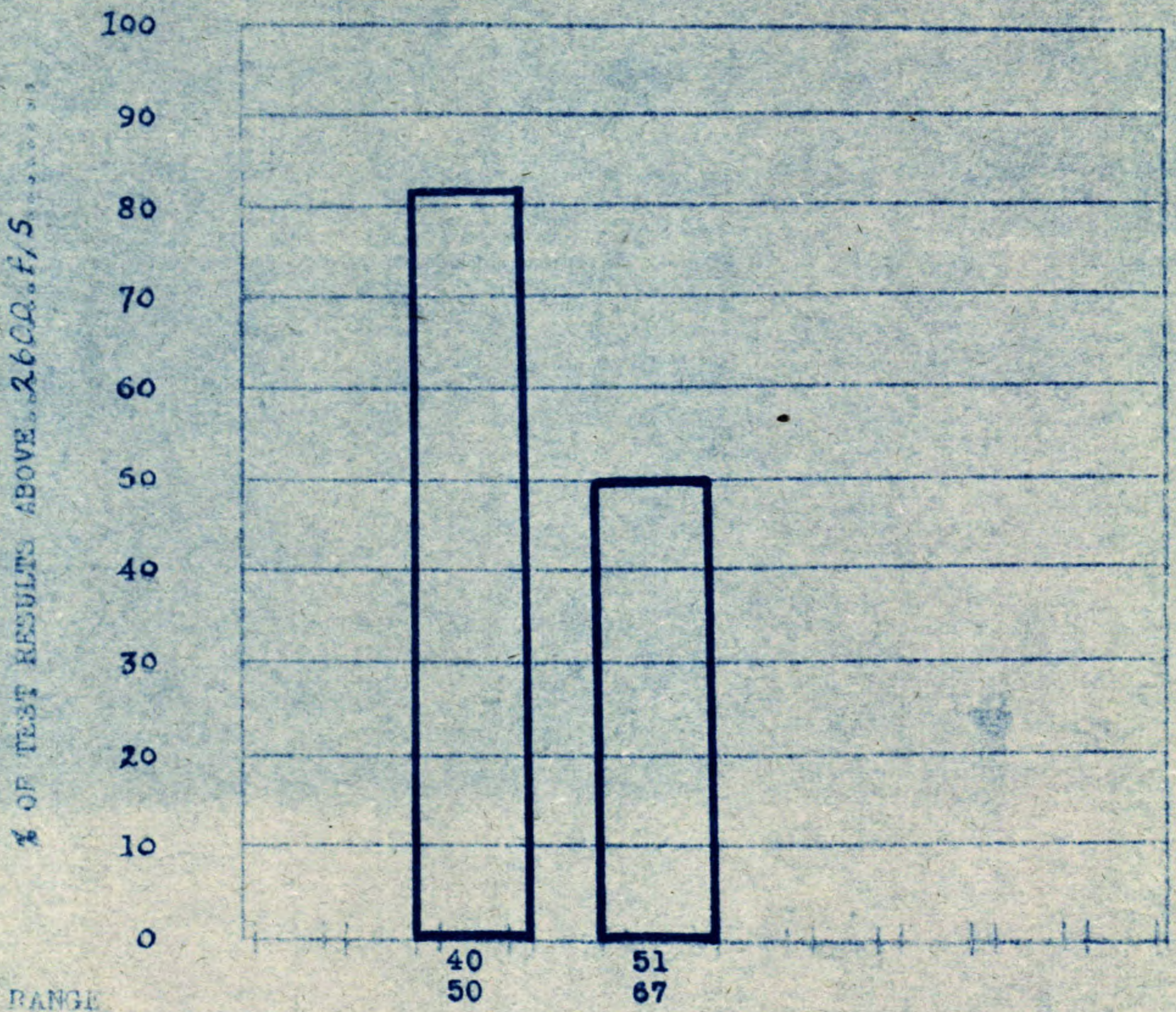
Number effect: .......... .1055 ..........

Significance:* .......... 87 %.

*(NOTE: This means that (100-87%) equals the percentage of the time the above ratio difference would occur due to chance.)

CORRELATION BETWEEN Izod ........... & Ballistic Limit

IN 3" Armour ...... FROM General ......




RANGE

| | | |
|---|---|---|
| No. above 2600 f/s: | 9 | 11 |
| Total number of test results: | 11 | 22 |
| Percentage above: | .82 | .50 |

Ratio difference: .32

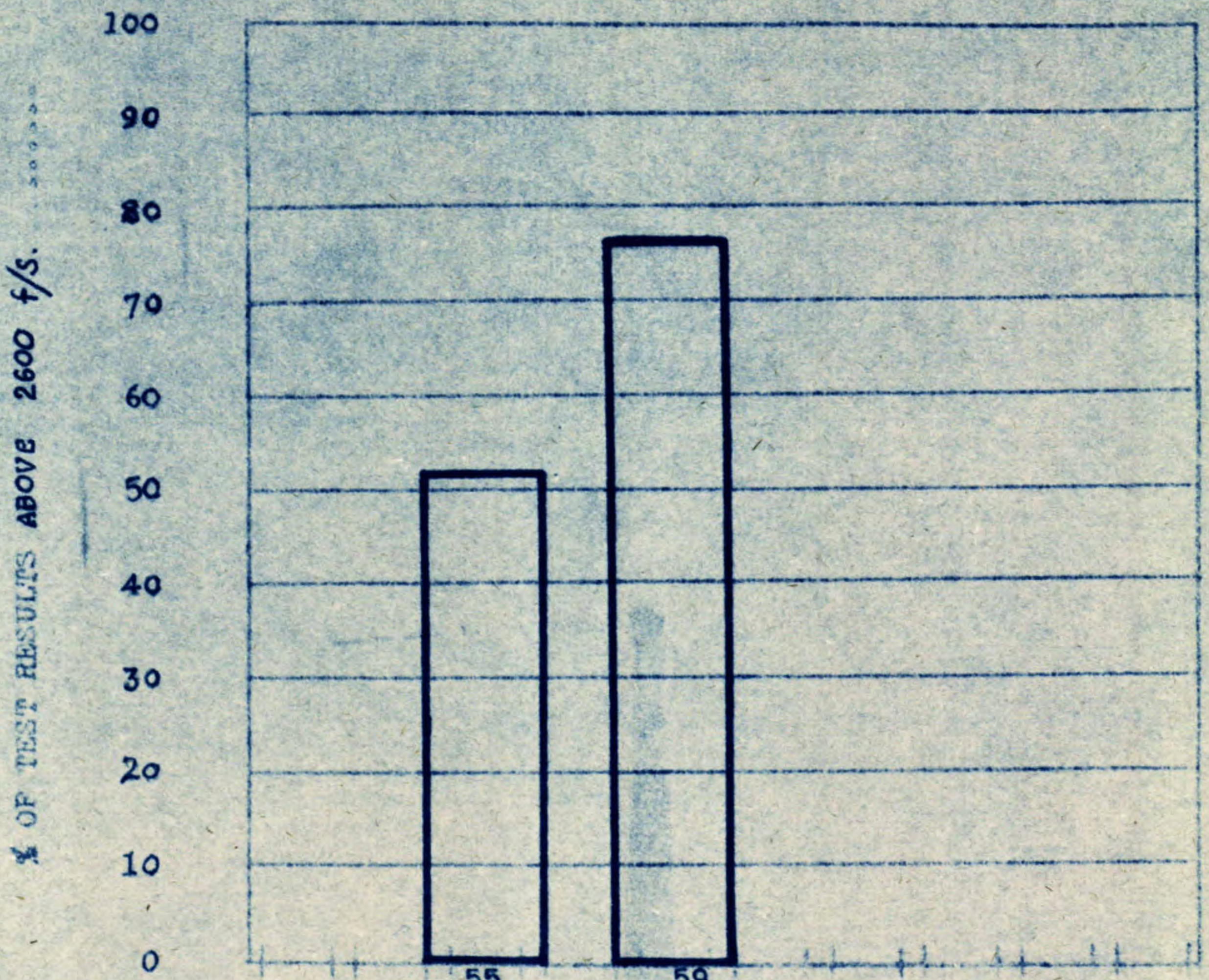
Number effect: .091 plus .0454 = .1364

Significance:* 85 %.

*(NOTE: This means that (100-85 %) equals the percentage of the time the above ratio difference would occur due to chance.)

CORRELATION BETWEEN **Molybdenum** . . . &. **Ballistic Limit** . .

IN. **3" Armour** . . . . . FROM. . **General** . . . . . .




| RANGE | .55 .58 | .59 .60 |
|---|---|---|
| No. above 2600 f/s: | 13 | 13 |
| Total number of test results: | 25 | 17 |
| Percentage above: | .52 | .76 |

Ratio difference: . . . . . . . . . . . . . .24 . . . . . . . . . . . . . . . . . . . .

Number effect: . . . .04 plus .06 = .1 . . . . . . . . . . . . . . . . . . . .

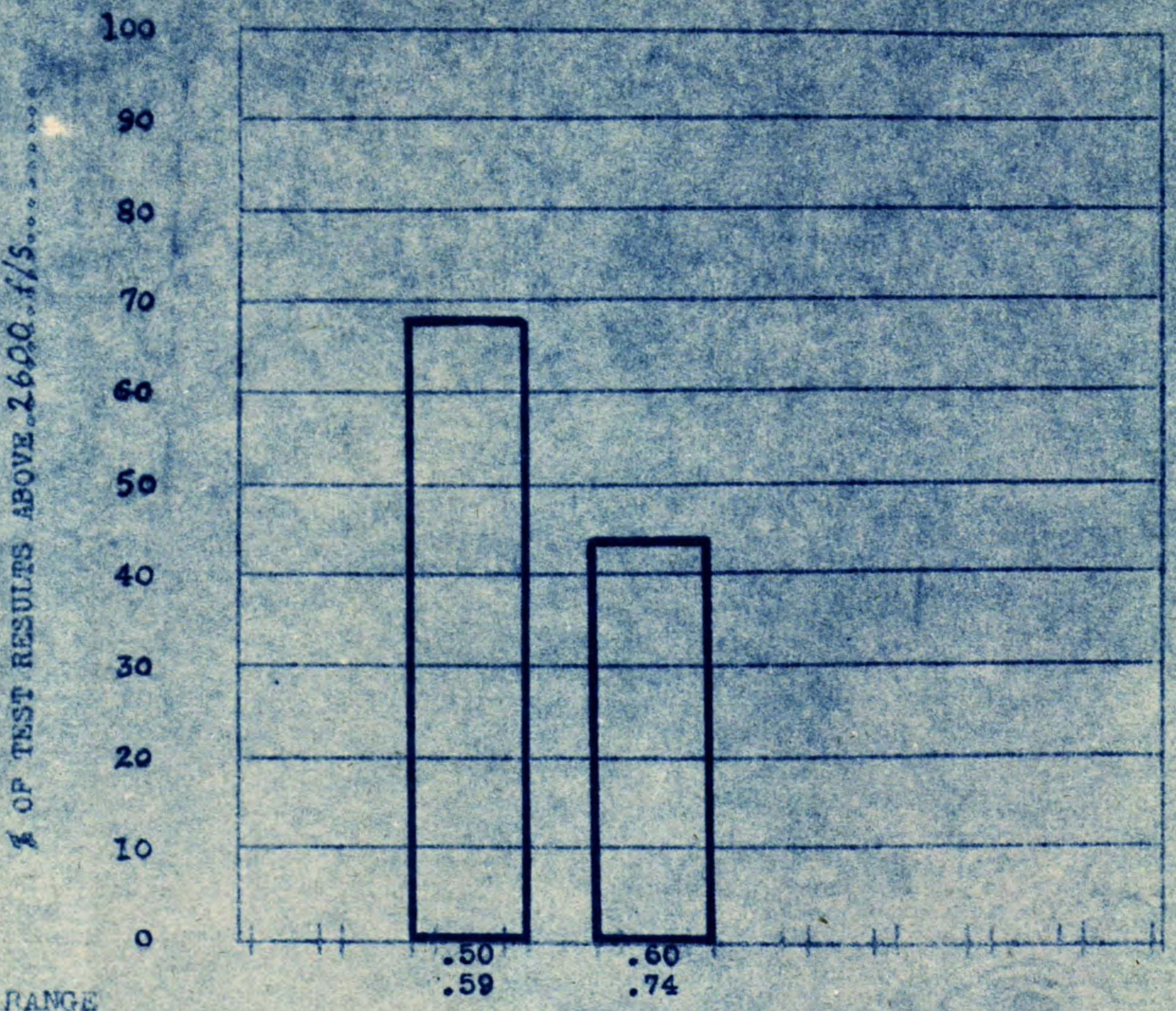
Significance:* . . . . . . . . . . 85 %.

*(NOTE: This means that (100-85%) equals the percentage of the time the above ratio difference would occur due to chance.)

Armour Statistics
Data Sheet No. 5.

CORRELATION BETWEEN **Manganese** ..... & **Ballistic Limit**....

IN. **3" Armour** ...... FROM. **General** .......




RANGE

| | | |
|---|---|---|
| No. above 2600 f/s: | 17 | 7 |
| Total number of test results: | 25 | 16 |
| Percentage above: | .68 | .44 |

Ratio difference: .24

Number effect: .04 plus .062 = .102

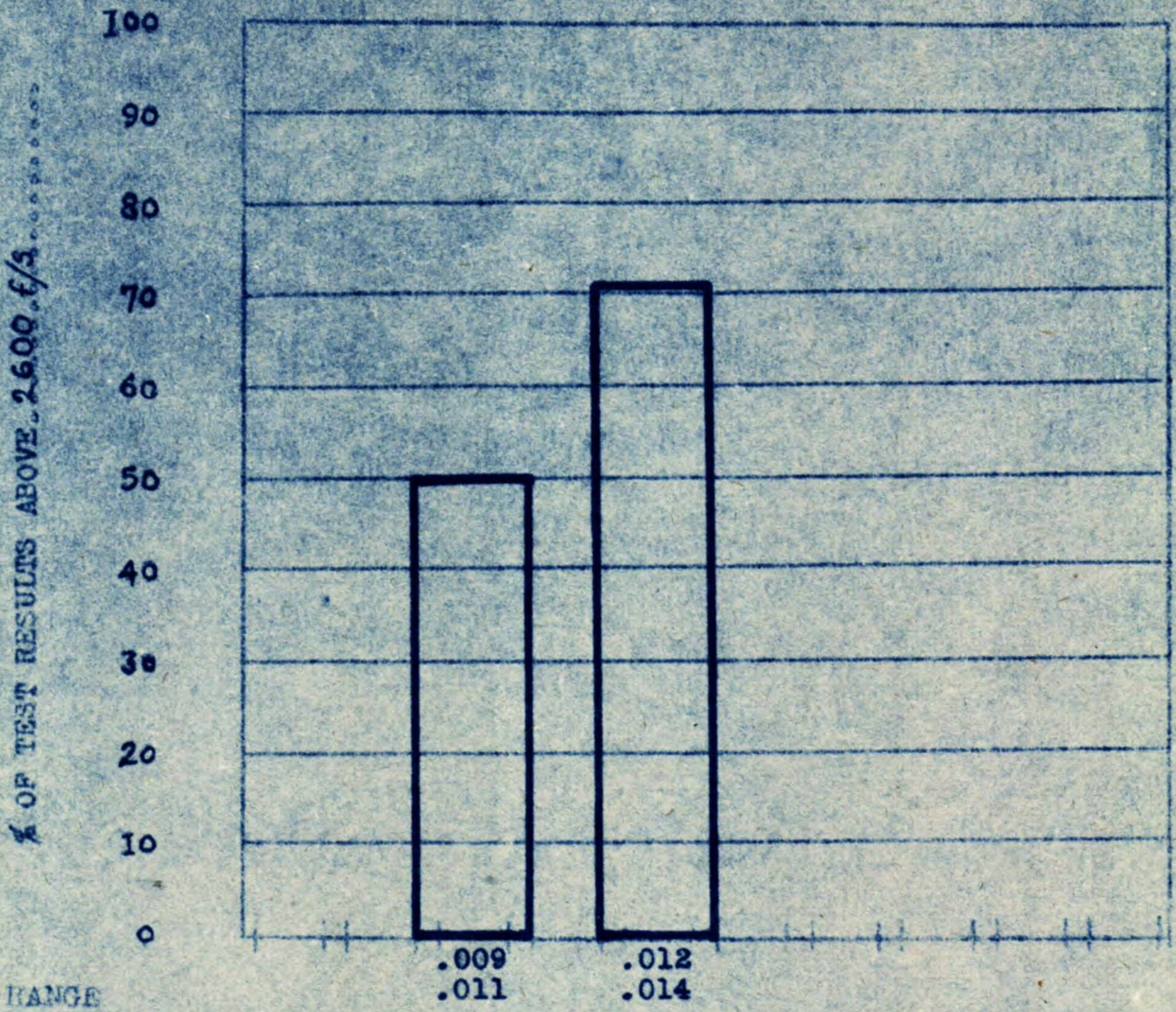
Significance:* 84 %.

*(NOTE: This means that (100-84 %) equals the percentage of the time the above ratio difference would occur due to chance.)

Armour Statistics
Data Sheet No. 5.

CORRELATION BETWEEN **Sulphur** & **Ballistic Limit**

IN 3" **Armour** FROM **General**




| | | |
|---|---|---|
| RANGE | .009 – .011 | .012 – .014 |
| No. above 2600 f/s: | 10 | 15 |
| Total number of test results: | 20 | 21 |
| Percentage above: | .50 | .71 |

Ratio difference: .21

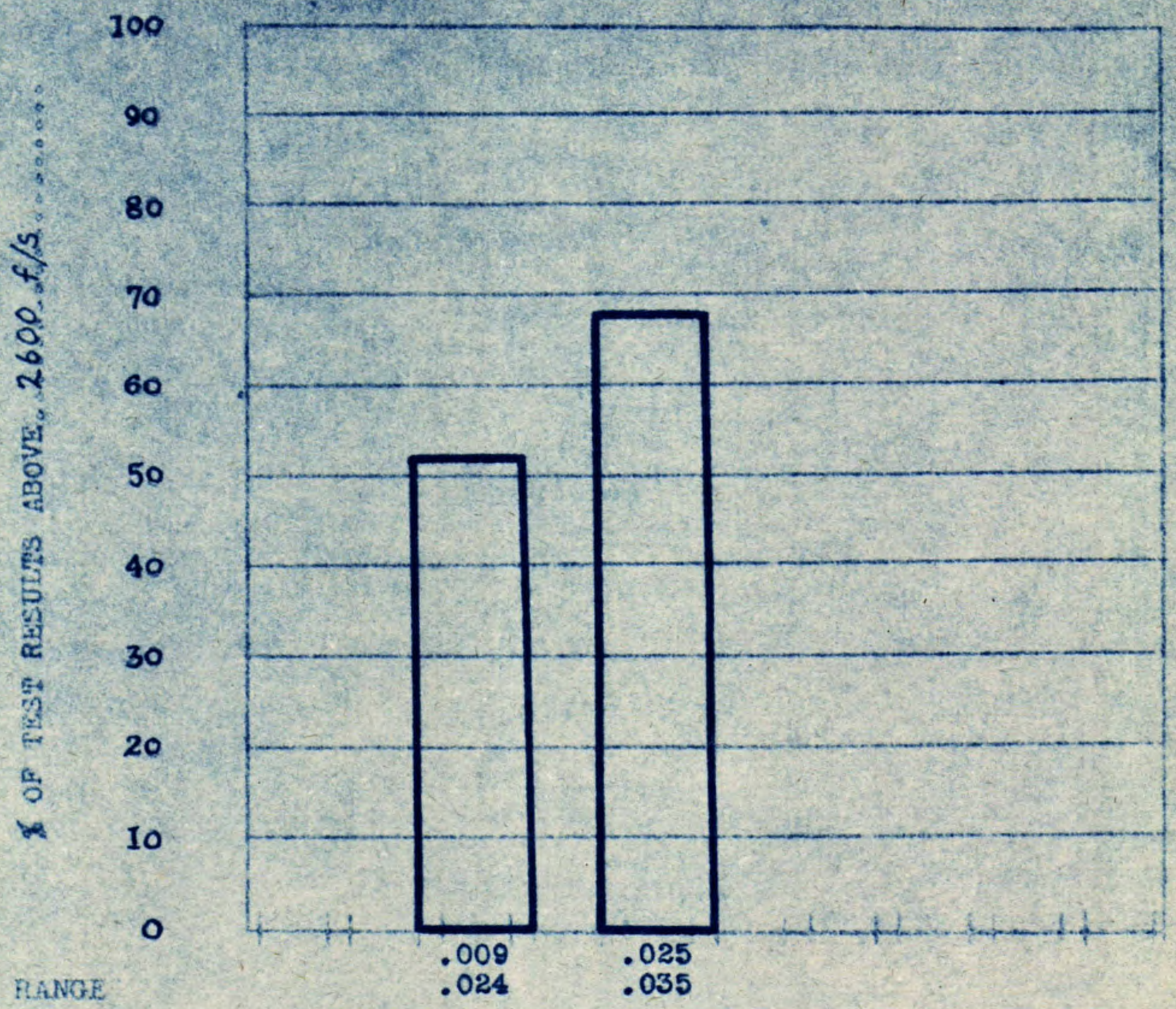
Number effect: .05 plus .0476 = .0976

Significance:* 80 %.

*(NOTE: This means that (100-80 %) equals the percentage of the time the above ratio difference would occur due to chance.)

CORRELATION BETWEEN **Phosphorus** ....... & **Ballistic Limit**

IN **3" Armour** ..... FROM **General** .......




| | | |
|---|---|---|
| RANGE | .009 – .024 | .025 – .035 |
| No. above 2600 f/s: | 12 | 13 |
| Total number of test results: | 23 | 19 |
| Percentage above: | .52 | .68 |

Ratio difference: ................ .16 ..........................

Number effect: ...... .043 + .052 = .095 ..........................

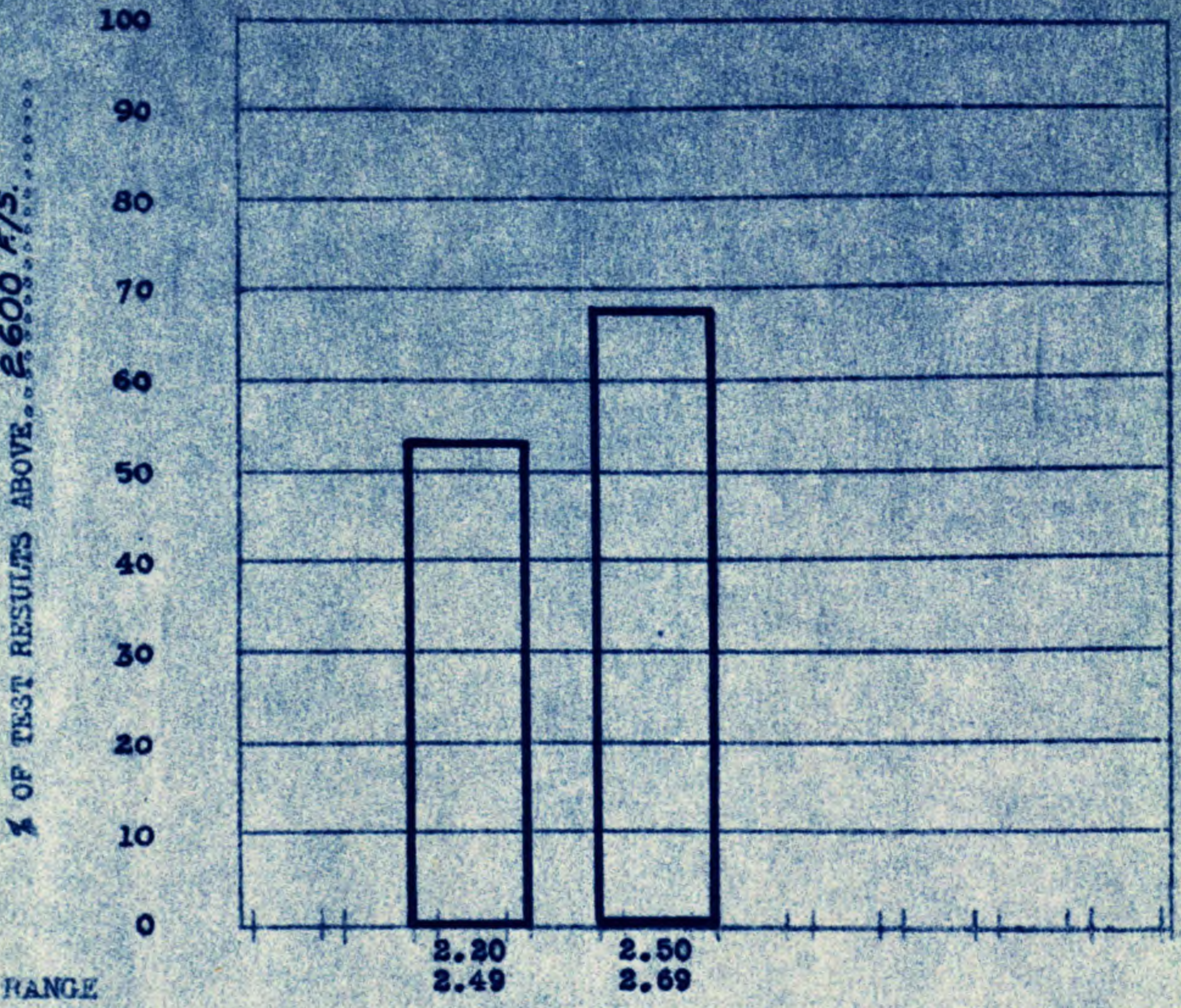
Significance:* ........ 65 %.

*(NOTE: This means that (100-65%) equals the percentage of the time the above ratio difference would occur due to chance.)

Armour Statistics
Data Sheet No. 5.

CORRELATION BETWEEN Chromium ..... & Balliatic Limit ..

IN. . 3" Armour ..... FROM. General ........




| | | |
|---|---|---|
| No. above 2600 f/s: | 9 | 15 |
| Total number of test results: | 17 | 22 |
| Percentage above: | .53 | .68 |

Ratio difference: .15

Number effect: .059 + .045 = .104

Significance:* 60 %.

*NOTE: This means that (100-60%) equals the percentage of the time the above ratio difference would occur due to chance.

Armour Statistics
Data Sheet No. 5.

Table I.

Summary of Ratio Differences

| Property | Most Desirable Part of Actual Operating Range | Significance (Per cent) |
|---|---|---|
| Brinell - | 268-279 | 99.85 |
| Carbon, p.c. - | 0.30-0.35 | 99 |
| Yield, p.s.i. - | 119,000-133,500 | 96.5 |
| Tensile, p.s.i. - | 142,000-148,000 | 95 |
| Silicon, p.c. - | 0.29-0.30 | 94 |
| Elongation, p.c. - | 9-15 | 92 |
| Reduction of area, p.c. - | 24-40 | 87 |
| Molybdenum, p.c. - | 0.59-0.60 | 85 |
| Izod, ft.lb. - | 40-50 | 85 |
| Manganese, p.c. - | 0.50-0.59 | 84 |
| Sulphur, p.c. - | 0.012-0.014 | 80 |
| Phosphorus, p.c. - | 0.025-0.035 | 65 |
| Chromium, p.c. - | 2.50-2.69 | 60 |

The thirteen properties of the plate which were recorded have been arranged in order of decreasing significance. The optimum operating ranges (for the period under investigation) have been outlined. The relative significance of heat treatment, chemical analysis and steel-making process can be inferred from the following arrangement of the properties according to their position in Table I:

(Continued on next page)

Table II.

| Order of Significance | Properties controlled by heat treatment. | Analysis | Properties connected with steel-making. |
|---|---|---|---|
| 1 | Brinell | | |
| 2 | | Carbon | |
| 3 | Yield | | |
| 4 | Tensile | | |
| 5 | | | Silicon |
| 6 | Elongation | | |
| 7 | Red. of area | | |
| 8 | | Molybdenum | |
| 9 | Izod | | |
| 10 | | Manganese | |
| 11 | | | Sulphur |
| 12 | | | Phosphorus |
| 13 | | Chromium | |

Prediction:

Having obtained an indication that control of armour plate properties in GENERAL steel depends mainly upon heat treatment, next upon analysis, and to a lesser extent on properties connected with steel-making, one then wishes to know, "Will application of the limits of Table I produce higher quality armour?"

Before attempting to apply any limits to production variables one should have a thorough understanding of the variable, what it represents and how closely it can be controlled.

Examples of Some Causes Which Affect Both Ballistic Limit and the Variable:

Brinell --

This is a measure of the drawing time and temperature as modified by section size and carbide stability.

(Continued on next page)

(Examples of Some Causes Which Affect Both Ballistic Limit and the Variable, cont'd) -

Yield -- Yield is affected by the cooling rate on quenching.

Silicon -- Both silicon and manganese reflect variation in deoxidation practice.

Thus a relationship between two properties (for example, silicon and ballistic limit) may be due to the effect of a common cause (deoxidation). It is quite possible that a slight change in melting, casting or heat-treating practice would change the optimum range of one or more variables. Therefore, before any worthwhile predictions can be based on operating data, a state of uniformity of operation must exist.

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Degree of Control:

An examination of plotted data revealed that a certain period showed a closer degree of control than the remainder. These samples represent Heats 4198 to 4288. It was decided to calculate the average and standard deviation for the three periods:

Period one, Heats 4098 to 4190

Period two, " 4198 to 4288

Period three, " 4310 to 4419

The results from this procedure are tabulated in Tables III and IV.

(Continued on next page)

(Degree of Control, cont'd) -

### Table III

Averages.

| Property | Period 1. | Period 2. | Period 3. |
|---|---|---|---|
| Ballistic limit - | 2552 | 2673 | 2600 |
| Brinell - | 260 | 269.5 | 269.5 |
| Yield, p.s.i. - | 109,000 | 120,000 | 138,000 |
| Tensile, p.s.i. - | 136,000 | 143,000 | 139,000 |
| Elongation, p.c. - | 16% | 15% | 14.5% |
| Red. in area, p.c. - | 42% | 38% | 37% |
| Izod, ft.lb. - | 57 | 51 | 47 |
| Carbon, p.c. - | 0.29 | 0.295 | 0.30 |
| Silicon, p.c. - | 0.315 | 0.30 | 0.32 |
| Manganese, p.c. - | 0.61 | 0.575 | 0.58 |
| Sulphur, p.c. - | 0.011 | 0.0115 | 0.0125 |
| Phosphorus, p.c. - | 0.024 | 0.023 | 0.014 |
| Molybdenum, p.c. - | 0.58 | 0.585 | 0.58 |
| Chromium, p.c. - | 2.46 | 2.55 | 2.54 |
| No. of results - | 19 | 13 | 8 |

### Table IV

Standard Deviations.

| Property | Period 1. | Period 2. | Period 3. |
|---|---|---|---|
| Ballistic limit - | 96 | 21.4 | 55 |
| Brinell - | 4.56 | 1.4 | 5 |
| Yield, p.s.i. - | 12,400 | 2,980 | 3,420 |
| Tensile, p.s.i. - | 10,330 | 1,875 | 4,675 |
| Elongation, p.c. - | 2.2 | 2.7 | 2.05 |
| Red. in area, p.c. - | 6.4 | 5.73 | 6.3 |
| Izod, ft.lb. - | 5.35 | 4.1 | 4.78 |
| Carbon, p.c. - | 0.024 | 0.006 | 0.01 |
| Silicon, p.c. - | 0.019 | 0.0076 | 0.0087 |
| Manganese, p.c. - | 0.048 | 0.026 | 0.035 |
| Sulphur, p.c. - | 0.00129 | 0.0009 | 0.00125 |
| Phosphorus, p.c. - | 0.0058 | 0.0032 | 0.0067 |
| Molybdenum, p.c. - | 0.02 | 0.007 | 0.007 |
| Chromium, p.c. - | 0.163 | 0.102 | 0.086 |
| No. of results - | 19 | 13 | 8 |

Probable Error:

The accuracy of averages may be reported as:

$$\text{Average} \pm \frac{3 \text{ standard deviations}}{\sqrt{N}};$$

the accuracy of standard deviations as:

$$\text{Standard deviation} \pm \frac{3 \text{ standard deviations}}{\sqrt{2N}}.$$

Distribution Characteristics:

The results of Table III show apparent differences which, if true, are significant. However, the small number of results does not give much weight to the conclusions which one is immediately tempted to formulate. It would seem that the high ballistic limits and the narrow range of ballistic limits encountered in Period 2 were directly associated with a greater degree of control over variations in physical and chemical properties.

It is highly probable that the following program when carried out will provide a considerable fund of information on armour plate:

Obtain operating data covering each successive 50 heats and determine, for ballistic limit and all measurable properties, the following distribution characteristics:

| Name | | Equation |
|---|---|---|
| Average | $\bar{X}$ | $= \frac{\Sigma X}{N}$ |
| Standard deviation | $\sigma$ | $= \sqrt{\frac{\Sigma (X - \bar{X})^2}{N}}$ |
| Skewness | $\pi_3$ | $= \frac{\Sigma (X - \bar{X})^3}{N}$ |
| Kurtosis | $\pi_4$ | $= \frac{\Sigma (X - \bar{X})^4}{N}$ |

KEY: $\Sigma$ - the sum of
- $X$ - a test result
- $N$ - the number of test results
- $\bar{X}$ - average of all test results

These measures will show the general nature of a process for the time interval examined and will make it

(Distribution Characteristics, cont'd) -

possible to compare the characteristics of different periods and different sources.

Standard Deviation -

This is a measure of the ability of the source to hold the property measured constant (or the spread of the results).

Skewness -

This is a measure of how far the distribution varies from a symmetrical distribution. If the skewness factor varies in successive periods, it may be suspected that bias has entered the sampling testing manufacturing procedure.

Kurtosis -

There will always be extreme results when a group of test data is examined. These results are caused by human carelessness, mechanical breakdowns, faulty material, power failures, etc., etc. The kurtosis factor is a measure of the frequency of extreme results. Thus an intangible operating characteristic can be quantitatively described.

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Conclusions:

1. STATISTICAL METHODS ARE TOOLS WHICH WILL GET INFORMATION QUICKLY. THIS INFORMATION WOULD OTHERWISE BE OBTAINED ONLY BY LONG PRACTICAL EXPERIENCE OR NOT AT ALL. WHETHER OR NOT ANY GOOD COMES FROM THE INFORMATION OBTAINED DEPENDS ENTIRELY UPON THOSE CHARGED WITH THE CONTROL OF MANUFACTURING OPERATIONS. ANY IMPROVEMENT OF ARMOUR PLATE

(Conclusions, cont'd) -

THAT IS MADE WILL BE DUE TO THE TIRELESS AND SKILLFUL EFFORTS OF THOSE ENGINEERS, METALLURGISTS AND SKILLED TECHNICAL PERSONNEL WHO ARE ENGAGED IN CONTROLLING MANUFACTURING OPERATIONS.

2. The ballistic limit of a plate for a projectile is the maximum velocity of the projectile which will not defeat the plate. The main purpose of armour manufacture is to obtain plate with the highest possible ballistic limit, consistent with other properties such as weldability, ease of fabrication, and resistance to shock.

3. A plate which is ideal for 2-pounder shot may be very poor when tested with 6-pounder shot. Larger projectiles therefore require softer plate for their defeat than do smaller projectiles. It is well known that the U. S. Army has reduced the hardness and the ballistic limit requirements of its armour so that satisfactory resistance to heavy projectiles could be obtained.

4. The data of this report have accepted the test with 37 mm. shot as the only criterion of excellence.

5. A measurable degree of correlation has been shown to exist between ballistic limit and the following properties:

Tensile strength

Yield point

| | | |
|---|---|---|
| Elongation | Impact strength | Reduction of area |
| Brinell hardness | Carbon | Silicon |
| Manganese | Sulphur | Phosphorus |
| Molybdenum | Chromium | |

(Continued on next page)

(Conclusions, cont'd) -

6. Since this correlation can be measured, it is possible to find out the most desirable operating range for each measurable variable. Since the above variables can be correlated with ballistic limit, it is highly probable that there are other measurements of physical property, microstructure, hardenability or process characteristics which can be correlated with armour properties.

7. It should be strongly emphasized that a relationship between a variable and the ballistic limit holds true only for the source from which it is drawn. Each source must be considered as an entirely separate problem.

8. Metallurgical processes are subject to trends. Properties of raw materials change, furnace refractories wear away, air humidity varies, moulding sand changes in properties, etc. For this reason, a relationship between a variable and ballistic limit will not remain constant, but will be subject to trends. Therefore successive periods must be analysed in order to keep informed of any changes in the fundamental laws controlling the process.

9. CORRELATION DOES NOT IMPLY CAUSE AND EFFECT. If a variable--for example, silicon--has a close relationship with ballistic limit, it may be due to some phase of the deoxidation process which affects both silicon and ballistic limit in a similar manner. If a variable, for example sulphur, shows a close relationship to ballistic limit, it may be due to a slag reaction that affects both sulphur and ballistic limit. The fact that a relationship exists is a powerful clue to the engineer, metallurgist, and skilled

(Conclusions, cont'd) -

personnel charged with the responsibility of controlling operating conditions.

Statistical methods only serve as sign posts to point out the path over which metallurgical operators must toil and struggle. If materials, equipment and man power are not able to hold variables to the limits pointed out by statistical methods, there is no point in obtaining the information.

10. The data analysed in this investigation show the advisability of shifting the limits of several variables as follows:

| Property | Median as found | Median recommended |
|---|---|---|
| Brinell | 268 | 273 |
| Carbon, p.c. | 0.29-0.30 | 0.325 |
| Yield, p.s.i.<br>Tensile, p.s.i. | 119,000<br>142,000 | 126,000<br>145,000 |
| Silicon, p.c. | 0.33 | 0.29-0.30 |
| Elongation, p.c. | 15% | 12% |
| Reduction of area, p.c. | 40-41% | 32% |

Each subsequent period of analysis will suggest further slight shifts of the desirable medians of test results. Thus all properties can gradually be shifted to their most desirable range. Of course, this is based on the use of 37 mm. shot for testing. Lighter or heavier projectiles would require different properties for their defeat.

11. A very low degree of correlation does not necessarily mean that there is no relationship between

(Conclusions, cont'd) -

ballistic limit and the variable in the present range of the variable. It may be that sampling or testing is carried out in such a way that the test is not representative of the material. Examples of this are:

Hardness tests on decarburized metal

Separately cast and heat-treated test pieces used for physical tests.

The engineer, metallurgist, and skilled personnel will be able to judge whether or not such is the case.

## 12. RECOMMENDED PROGRAM -

In view of the information obtained up to this point it would seem advisable to set up a statistical program for each source of armour so that use could be made of information now lying dormant in ballistic and metallurgical test records. An outline of such a program is therefore suggested:

### (a) Determine Ideal Operating Ranges

Use the ratio difference method to show which variables are most closely related to ballistic limit, also the desirable control point for each variable. Determine these relationships at regular intervals (every month, every 50 heats, etc.).

### (b) Set Up Practical Control Limit Charts

For each variable construct a chart so that results can be plotted in chronological order. The chart should have a centre line and high and low limits. Consider Brinell hardness, for example. The data of this report suggest that a centre line of 273 Brinell should be used. High and low limits may be arbitrarily applied but it is

(Conclusions, cont'd) -

probably better to use limits based on previous records. If the data of Period 1 (Page 28) were used as a guide it could be inferred that there was a reasonable chance of controlling within 273 ± 3 X 4.5 (3 sigma limits). The low limit would then be 260 and the high limit 286 Brinell. If the data of Period 2 were used as a guide the low limit would be 269 and the high limit 277. There are many practical considerations involved when limits are placed on a variable. Wide limits mean a variation in ballistic limits, and narrow limits increase the cost of the material and tend to slow down production. The purpose of these control limit charts is to show when action is necessary to correct any tendency to deviate from the limits proven to be the most desirable. Thus each test result can be interpreted as O.K., bad, or of little significance, according to immediate past experience.

(c) Periodic Revision of Control Limit Charts

As each successive period of statistical analysis brings out more information, changes can be made in the control charts. Eventually each property will be brought into it's optimum range and the process will reach an equilibrium.

(d) Statistical Control Charts

When an equilibrium is reached, the process should be under statistical control. At this point statistical quality control can be put into effect. When the process is under statistical control, it is confidently expected that A REDUCTION CAN BE MADE IN THE NUMBER OF FIRING TESTS, SINCE NON-DESTRUCTIVE TESTS WILL SERVE AS SATISFACTORY INDICATORS OF ARMOUR QUALITY.

Acknowledgment:

We are indebted to the following individuals for their counsel and assistance in finding a method of attack on the armour plate problem:

Major Leslie E. Simon, of the Ordnance Department of the U. S. Army.

W. E. Deming, of the U. S. Census Bureau.

E. M. Schrock, of the Carnegie Illinois Steel Co.

Summary:

This report has indicated briefly some possibilities of the statistical analysis of armour plate manufacturing data. Manufacturers can, by using statistical methods, achieve the following:

1. Determine the most significant variables in their process.
2. By placing these variables in their ideal operating range, determine statistically the effect of minor variables.
3. Once major and minor variables are properly adjusted, trends or tendencies in the process under control may be noted. These trends or tendencies can be corrected before they impair armour quality.
4. General improvement in ballistic properties of the plate can be made.

Once the process is under control the number of ballistic tests may be greatly reduced. In spite of the

(Summary, concluded) -

fewer tests a better quality of plate can be made.

Since the present process is statistically out of control the ability of selected armour test plates to predict the quality of succeeding heats of plate is very doubtful. Actual firing test results support this statement.

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