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REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1537.

A New Method of Determining the Projectile Penetration Resistance of Armour Plate.

(Copy No. 14.)

Abstract

After studying ballistic records on $1\frac{1}{2}$-inch armour plate, a new method of determining resistance of armour to penetration was proposed. It is possible that this method may be more accurate and more economical than the Ballistic Limit method. The damage done to the face of a plate is measured and the plate is given a face damage rating. Only one shot is needed to test a plate by this method.

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

CANADA

DEPARTMENT
OF
MINES AND RESOURCES

Mines and Geology Branch

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Origin of Project and Purpose of Investigation:

This report is a part of the 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.

Ballistic Reports:

In testing $1\frac{1}{2}$-inch armour, a 2-pdr. shot is fired at right angles to the plate. The results of this operation which are recorded are:

(1) The speed of each shot, in feet per second.

(2) The depth of penetration into the face of the plate by each shot.

(3) The height of the bulge raised on the back of the plate.

(4) The extent of cracking on the bulge.

(5) The nature of the hole made by a shot passing completely through the plate.

(6) From the shots fired, an estimate of the speed required to defeat the plate is obtained. This is the ballistic limit.

In determining ballistic limit an attempt is made to bracket two shots so that one will not penetrate and the next at a higher velocity will penetrate. The speeds of these two shots are then averaged, and the average is called the ballistic limit.

The accuracy of the ballistic limit is equal to:

$$\pm \frac{\text{distance between bracketing shots}}{2}$$

If the bracketing shots are 70 ft./sec. apart, then the accuracy of a ballistic limit so determined is within ± 35 ft./sec. Figure 1 shows the distribution of the spread (in feet per second) of the bracketing shots used to determine the ballistic limits on the armour described in this report. Note that differences as great at 70 ft./sec. occur. In U.S. practice* a maximum spread of 35 feet per second is specified. This results in an accuracy greater than ± 17.5 ft./sec. in reported ballistic limits.

Figure 2 shows the ballistic limits plotted in groups

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* A Discussion of Summarization of Cast Armour Quality Control Chart R-11, Aberdeen Proving Grounds, Maryland.

(Ballistic Reports, cont'd) -

of four. (The grouping list shown on Page 19 gives the plate numbers included in each group). The variation is such that within four successive test plates a difference as great as 137 ft./sec. in ballistic limit may normally occur. The ballistic limit of the armour was not under statistical control. In section marked 2 the ballistic limits were definitely above average, and in the section marked 3 there was a run of low results. Since runs above and below average of this length rarely occur due to chance, we are justified in stating that three different processes* were used, viz.,

Groups								
1-5,	Period 1 -	Manufacturing	and/or	testing	method	A	was	used,
6-14,	Period 2 -	"	and/or	"	"	B	"	" ,
15-20,	Period 3 -	"	and/or	"	"	C	"	" ,

The exact nature of the differences in process or inspection technique in the three periods can only be explained by those familiar with these processes.

A comparison of Quality Control Charts for chemical and physical tests during the trial period will give some clues to the changes made in the process.

Face Damage Factor:

Noting that the depth of penetration of each shot was recorded, it was decided to plot Face Damage against velocity of shot. Figure 3 shows these data in scatterplot form. An estimating equation was derived which describes this phenomena as follows:

$$X = \frac{Y - 585}{26}$$

when X = depth of penetration in 1/16th second
Y = velocity of shot in ft./sec.**

From Figure 3 it can be seen that the amount of

* Statistically speaking, the product differed and therefore the process must have changed.

** For methods of deriving estimating equations see "Applied General Statistics," by Coxton & Cowden.

(Face Damage Factor, cont'd) -

penetration varies above and below the given equation. The plate could be rated according to its deviation from this Thus, a plate struck by a shot travelling at 1362 ft./sec. has a calculated penetration of 30/16 in. If the actual penetration was 28/16 in., the plate is 2/16 in. better than average. It was decided to use the difference between calculated and actual penetration as a rating factor for face damage. A plate that is 2/16 in. better than average is given a face damage factor of +2.

In Figure 4, face damage factors are plotted in groups of four. It is immediately evident that runs above and below average in face damage parallel those in ballistic limit. This would lead to the conclusion that the quality of armour might be predicted by the face damage factor.

Back Damage Factor:

Figure 5 shows back damage results plotted against velocities of shot. The average condition is estimated to be

$$X = \frac{Y - 948}{45},$$

where X = height of bulge on back of plate, and
Y = velocity of shot.

Back damage does not necessarily correlate to face damage. Therefore the two phenomena are considered separately.

In Figure 6 the back damage factors are plotted in quality control chart form. The back damage factor is the difference between actual height of bulge and that calculated from the above equation. A back damage factor of minus 1 indicates that the bulge is 1/16 in. larger than the estimations equation would indicate.

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Back Crackage:

A survey of firing records indicated that 40 per cent of the bulges of 8/16 in. in height were cracked, 90 per cent of the 9/16 in. bulges were cracked and all bulges 10/16 in. and greater were cracked. Figure 7 shows the frequency of cracking for bulges of different sizes.

For purposes of comparison it was decided to call plates which were not cracked with an 8/16 in. back damage GOOD. Plates which cracked with an 8/16 in. back damage are called BAD. This nomenclature will be used in correlating armour properties against decarburization and inclusions.

Hypothesis:

Summarizing, then, one shot fired against a plate will give the following information:

(1) Face damage factor.
(2) Back damage factor.
(3) Back cracking characteristic.

This information may be enough to rate the plate as:

(a) Better than average,
(b) Worse than average, or
(c) Similar to that previously accepted.

Before face damage factor can be accepted as an alternate for ballistic limit, it must be shown that:

(1) Face damage factor correlates with ballistic limit, and

(2) Face damage factor and ballistic limit are both correlated to the same metallurgical tests in the same way.

Correlation with ballistic limit alone is not sufficient evidence that face damage factor is a satisfactory substitute. In order to prove that face damage factor measures the same phenomena, it must be shown that it correlates with properties known to affect ballistic limit.

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Correlation Between Face Damage Factor and Ballistic Limit:

A comparison between Figures 2 and 4 shows that a high run of face damage factor coincides with a high run of ballistic limit. Also that group 15-20 are all below average in both face damage factor and ballistic limit. This indicates that the tests are comparable.

Correlation Between Ballistic Limit and Physical Tests:

The following physical properties were definitely correlated to ballistic limit and the optimum ranges are indicated:

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

The graphs on Pages 15 and 16 show these relationships.

Correlation Between Face Damage Factor and Physical Tests:

All physical tests were correlated with the face damage factor and the optimum ranges are:

Yield	-	53-57.1 tons.
Tensile	-	61.7-65 tons.
Izod	-	48-65 ft.-lb.
Brinell	-	270-302.
Elongation	-	19.5-21.5 per cent.
Reduction of area	-	62-65 per cent.

The graphs on Page 17 show that the above relationships between face damage factor and physical properties are of a higher order than that between ballistic limit and physical properties. This means that face damage factor is a more accurately determined value than ballistic limit.

Back Damage Correlated to Physical Properties:

Page 19 shows the relationship between back damage and physical properties. Optimum conditions are:

Yield	-	52.8-57.1 tons.
Tensile	-	61.5-65 tons.
B.H.N.	-	286-302.
Izod	-	48-65.

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Discussion:

The question might be raised, Why not use physical tests as the acceptance criterion for armour? Static tests do not always indicate the behaviour of a plate under ballistic impact. The static and dynamic properties are correlated but the correlation is not exact enough to substitute physical tests for ballistic tests.

Since all plate cannot be tested ballistically, physical tests are used to indicate that manufacturing practice is uniform.

It is recommended that only one shot need be fired in order to obtain a measurement of the resistance to penetration. This could save considerable time and material in the testing of armour plate. The test would consist of firing one shot at a velocity between 1280 to 1440 ft./sec. and comparing the actual face damage penetration with the calculated penetration. If the difference is within ± 2/16 in., accept the plate.

This suggestion is offered for the serious consideration of Ordnance officers engaged in testing armour plate.

CONCLUSIONS:

Evidence has been presented to show that face damage factor indicates the same thing that ballistic limit does, i.e., resistance to penetration.

Resistance to shock is another property of armour and is not necessarily related to resistance to penetration.

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HHF:GHB.

(Pages 8 to 14 are charts;)
(Pages 15 to 18 are graphs;)
(Page 19 is grouping list.)

FIG. 7

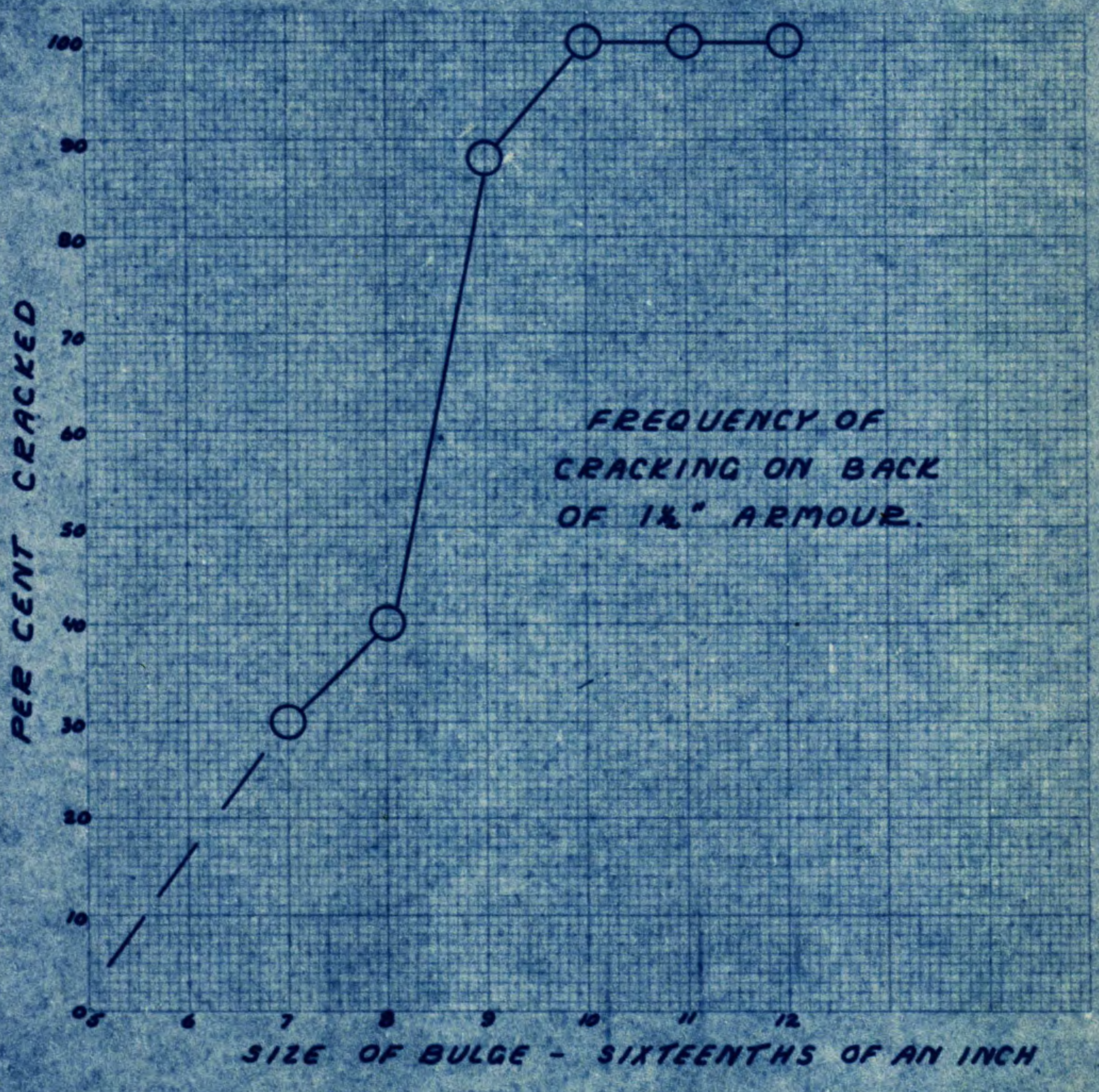
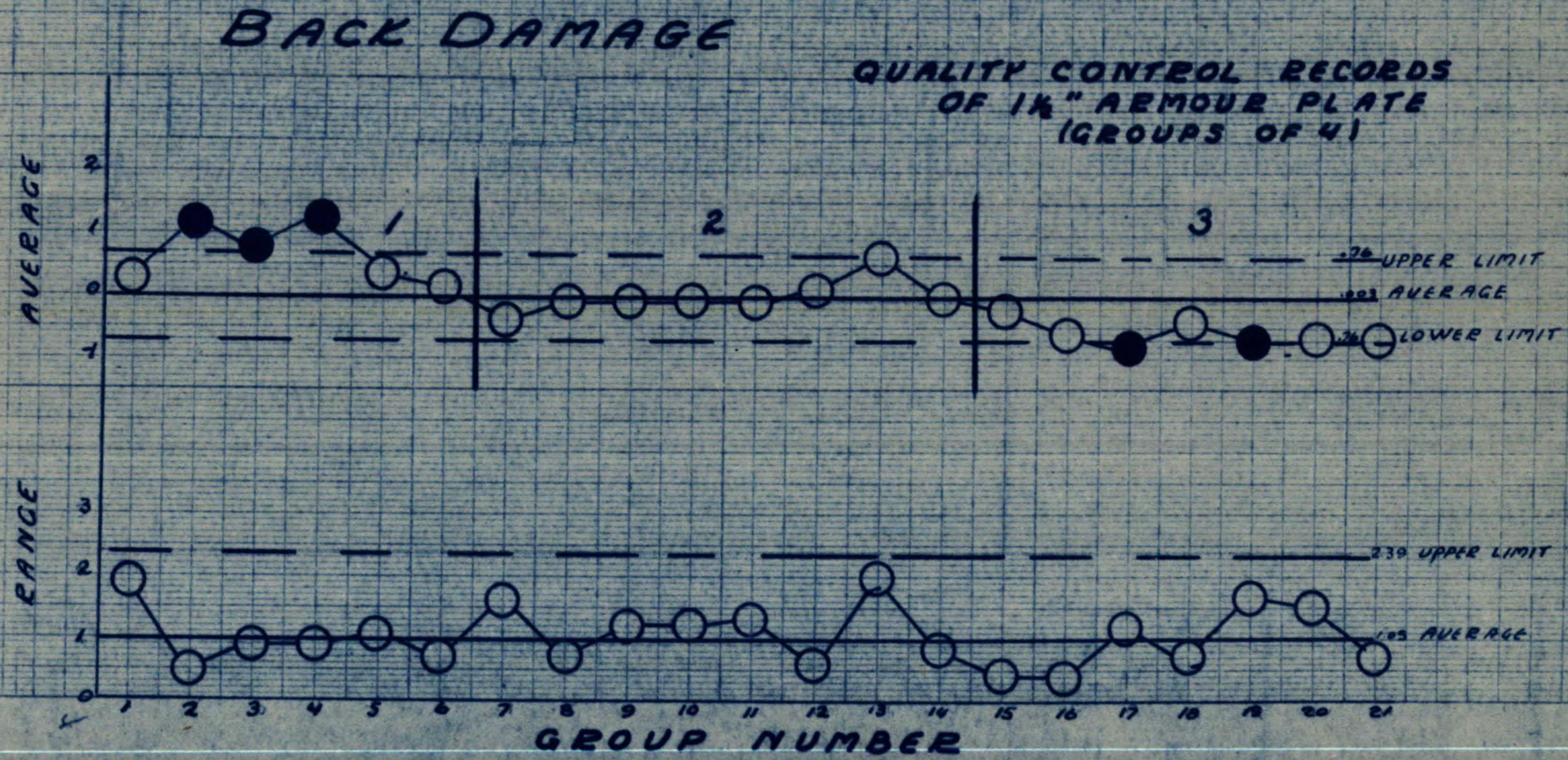

FREQUENCY OF
CRACKING ON BACK
OF 1½" ARMOUR.
PER CENT CRACKED
100
90
80
70
60
50
40
30
20
10
0
5
6
7
8
9
10
11
12
SIZE OF BULGE - SIXTEENTHS OF AN INCH

FIG 6.



BACK DAMAGE
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
(GROUPS OF 4)
AVERAGE
RANGE
1
2
3
.76 UPPER LIMIT
.003 AVERAGE
.76 LOWER LIMIT
2.39 UPPER LIMIT
1.05 AVERAGE
GROUP NUMBER

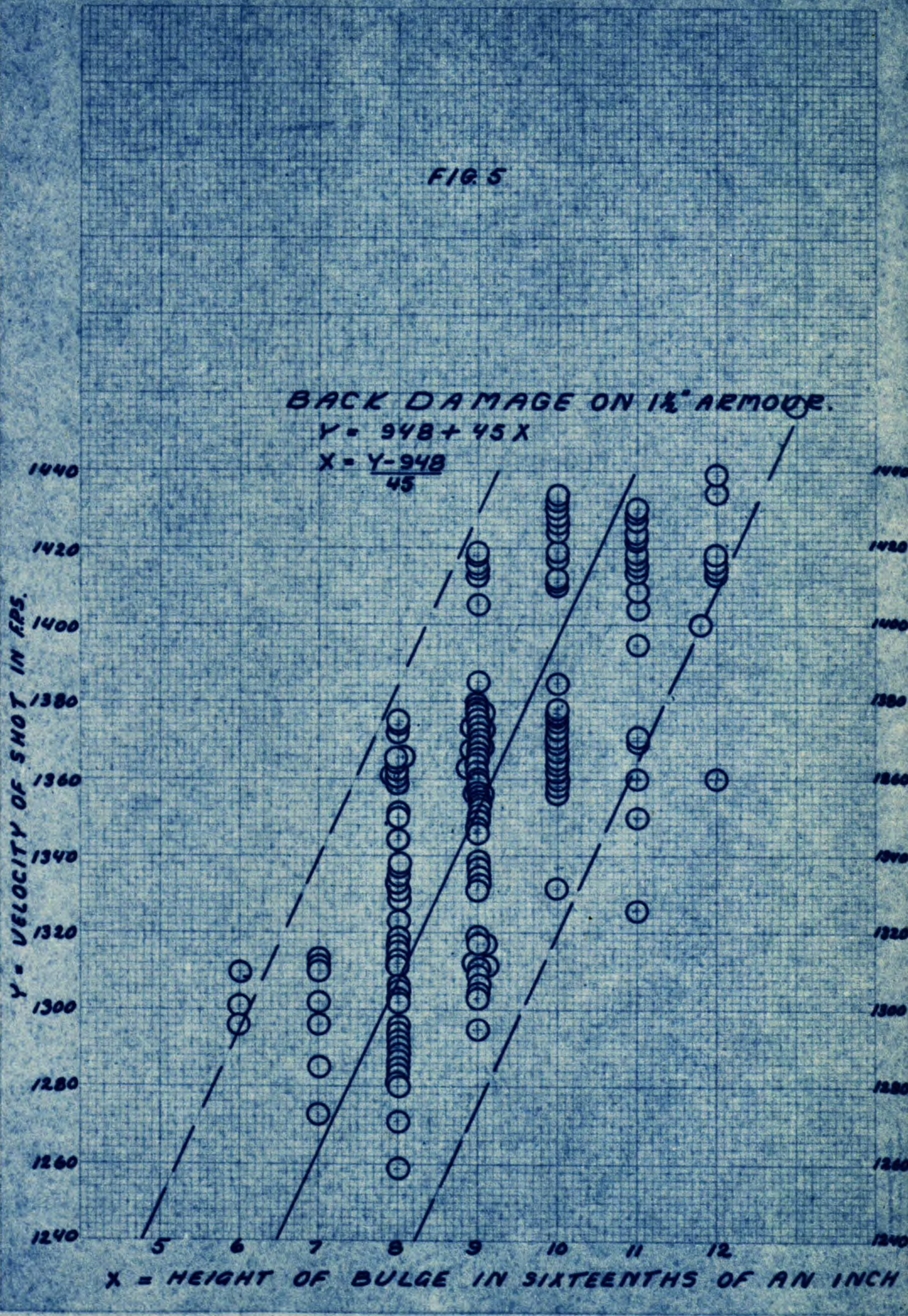


FIG. 5
BACK DAMAGE ON 1½" ARMOUR.
Y = 948 + 45 X
X = Y-948 / 45
Y = VELOCITY OF SHOT IN F.P.S.
1240
1260
1280
1300
1320
1340
1360
1380
1400
1420
1440
5
6
7
8
9
10
11
12
X = HEIGHT OF BULGE IN SIXTEENTHS OF AN INCH

FIG 4.

FACE DAMAGE

QUALITY CONTROL RECORDS OF 1½" ARMOUR PLATE

GROUPS OF 4

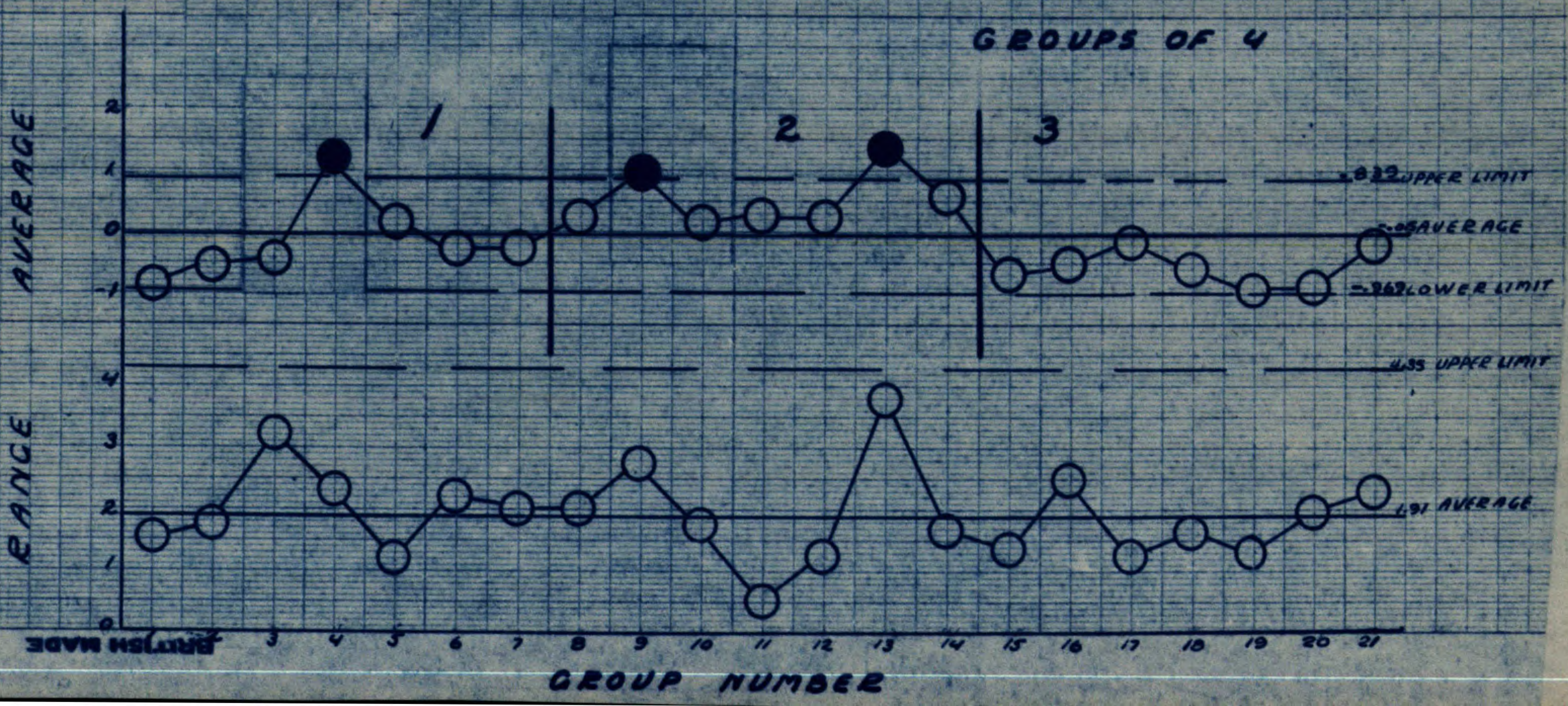
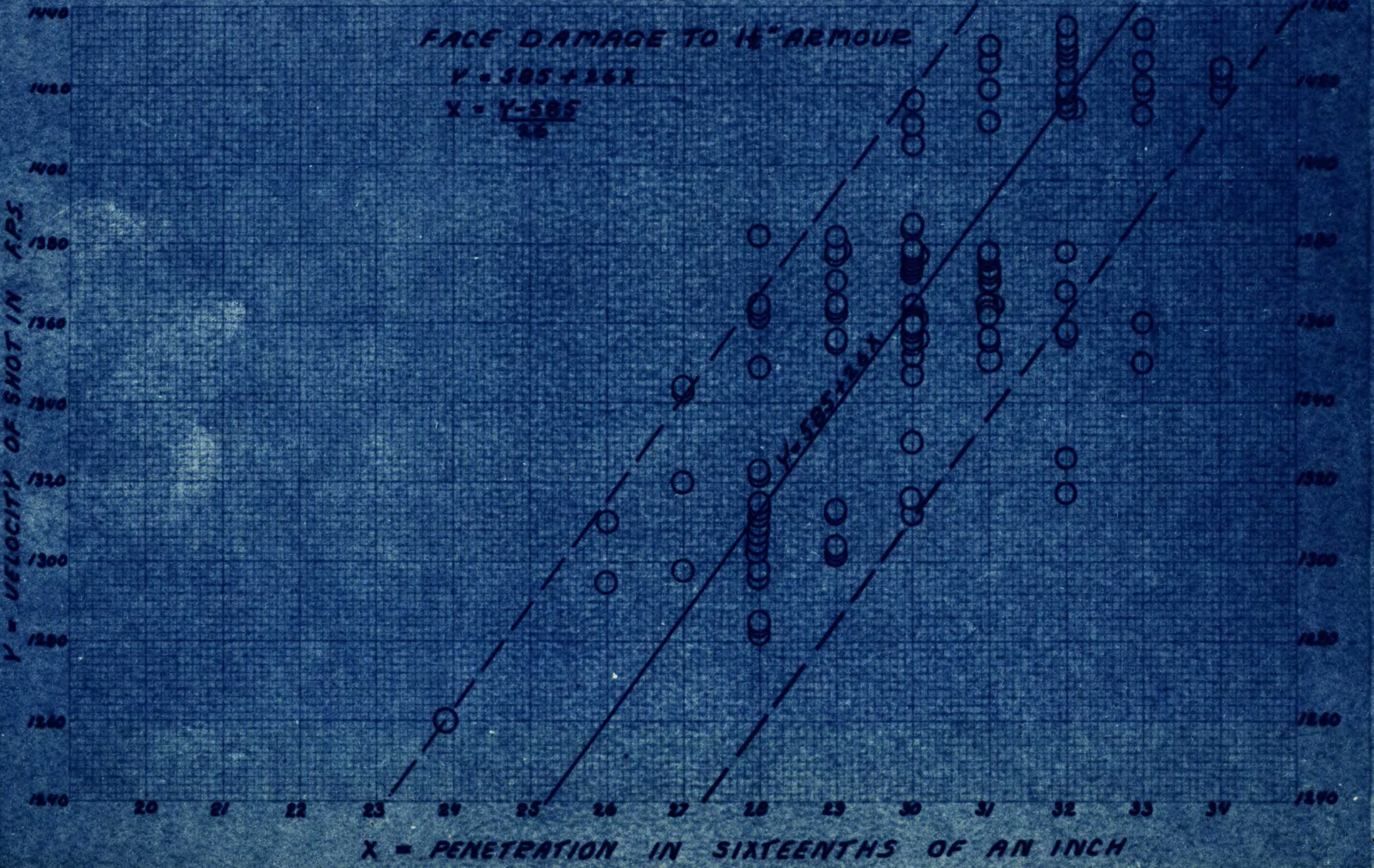
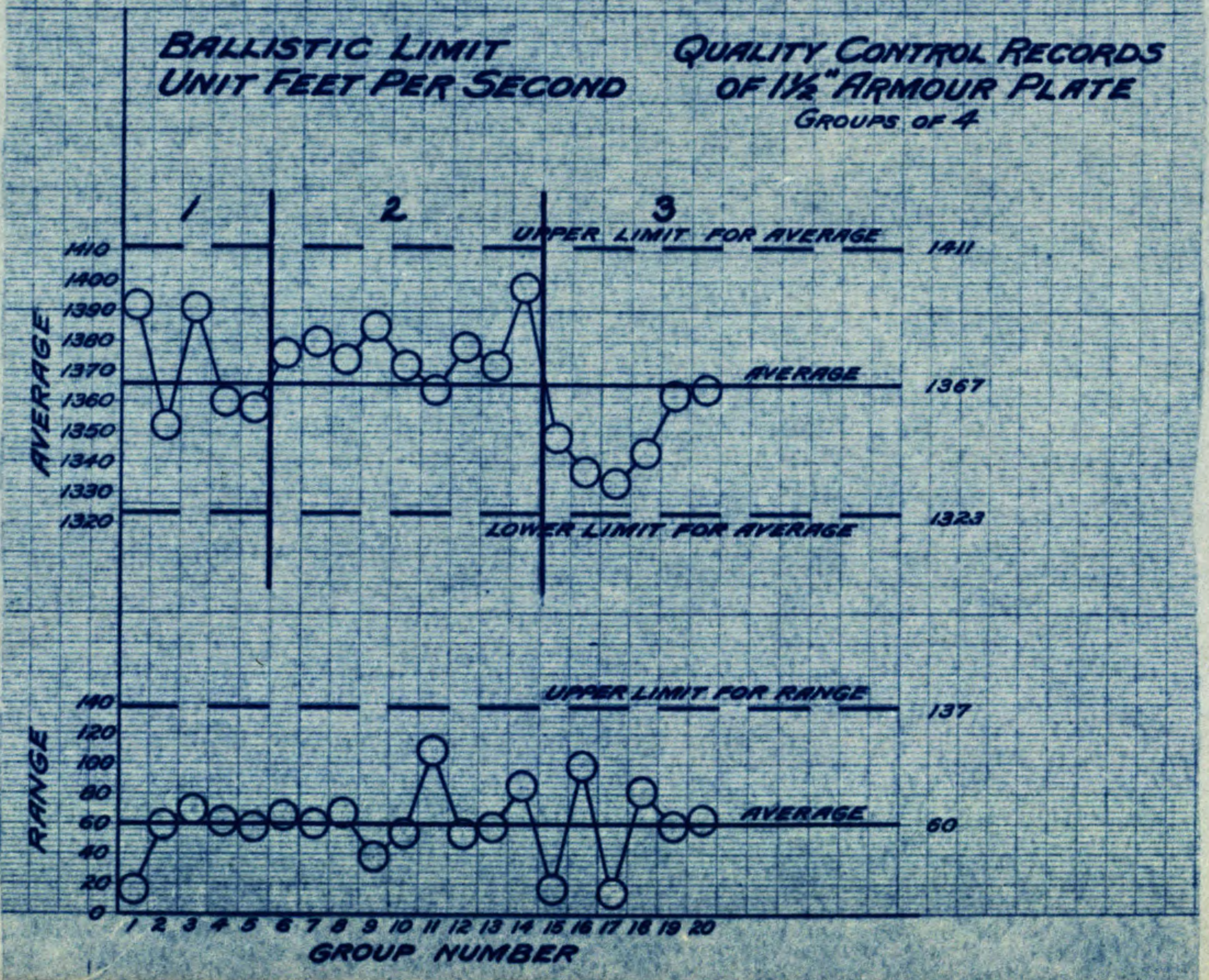


FIG. 3.


FACE DAMAGE TO 1½" ARMOUR
Y = 585 + 26X
X = (Y-585)/26
Y=585+26X
Y = VELOCITY OF SHOT IN F.P.S.
X = PENETRATION IN SIXTEENTHS OF AN INCH
1440
1420
1400
1380
1360
1340
1320
1300
1280
1260
1240
20 21 22 23 24 25 26 27 28 29 30 31 32 33 34

(Page 10)

FIG 2.


BALLISTIC LIMIT
UNIT FEET PER SECOND
QUALITY CONTROL RECORDS
OF 1½" ARMOUR PLATE
GROUPS OF 4
1
2
3
UPPER LIMIT FOR AVERAGE
1411
AVERAGE
1367
LOWER LIMIT FOR AVERAGE
1323
1410
1400
1390
1380
1370
1360
1350
1340
1330
1320
AVERAGE
UPPER LIMIT FOR RANGE
137
AVERAGE
60
140
120
100
80
60
40
20
0
RANGE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
GROUP NUMBER

(Page 9)

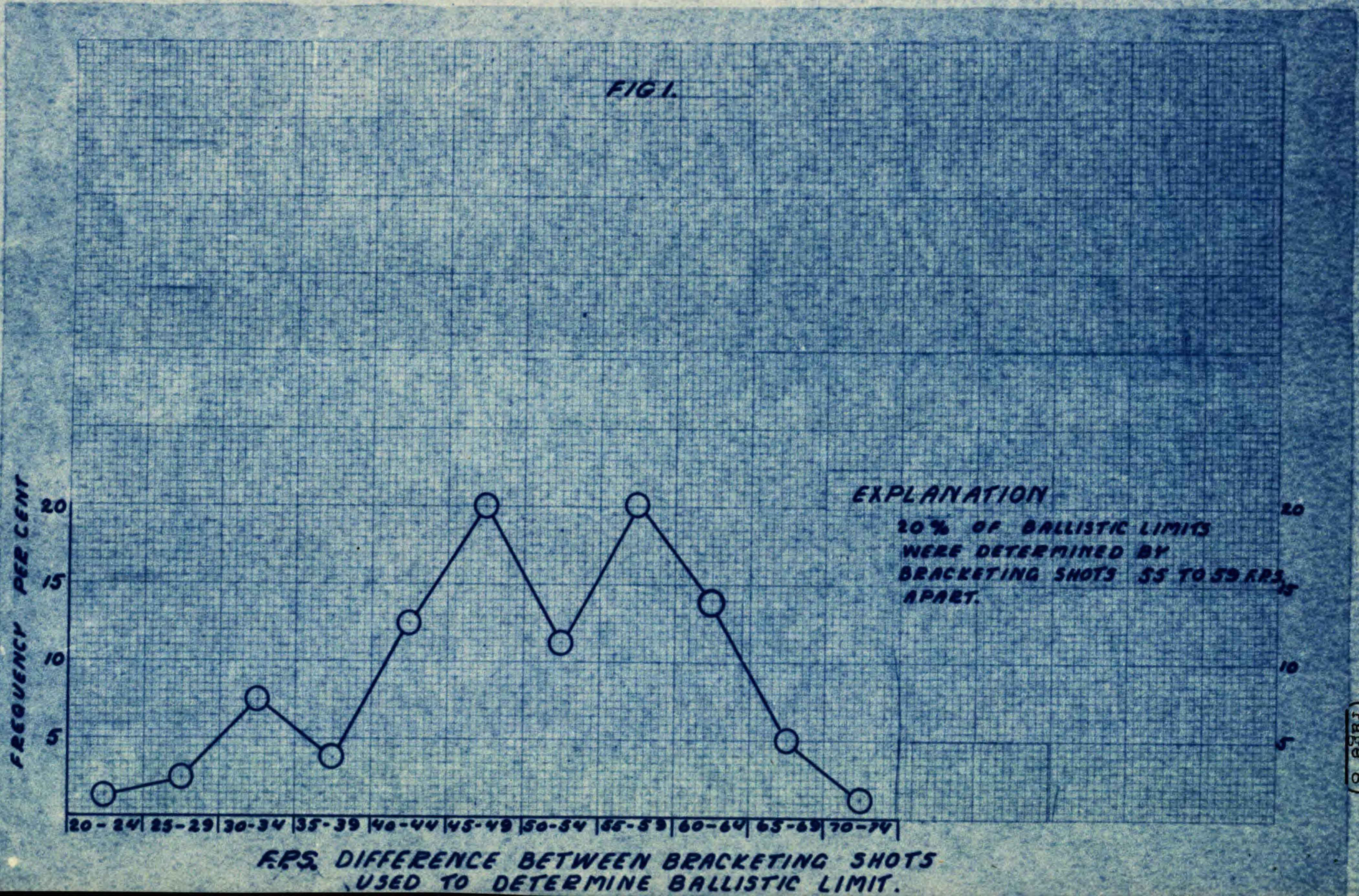
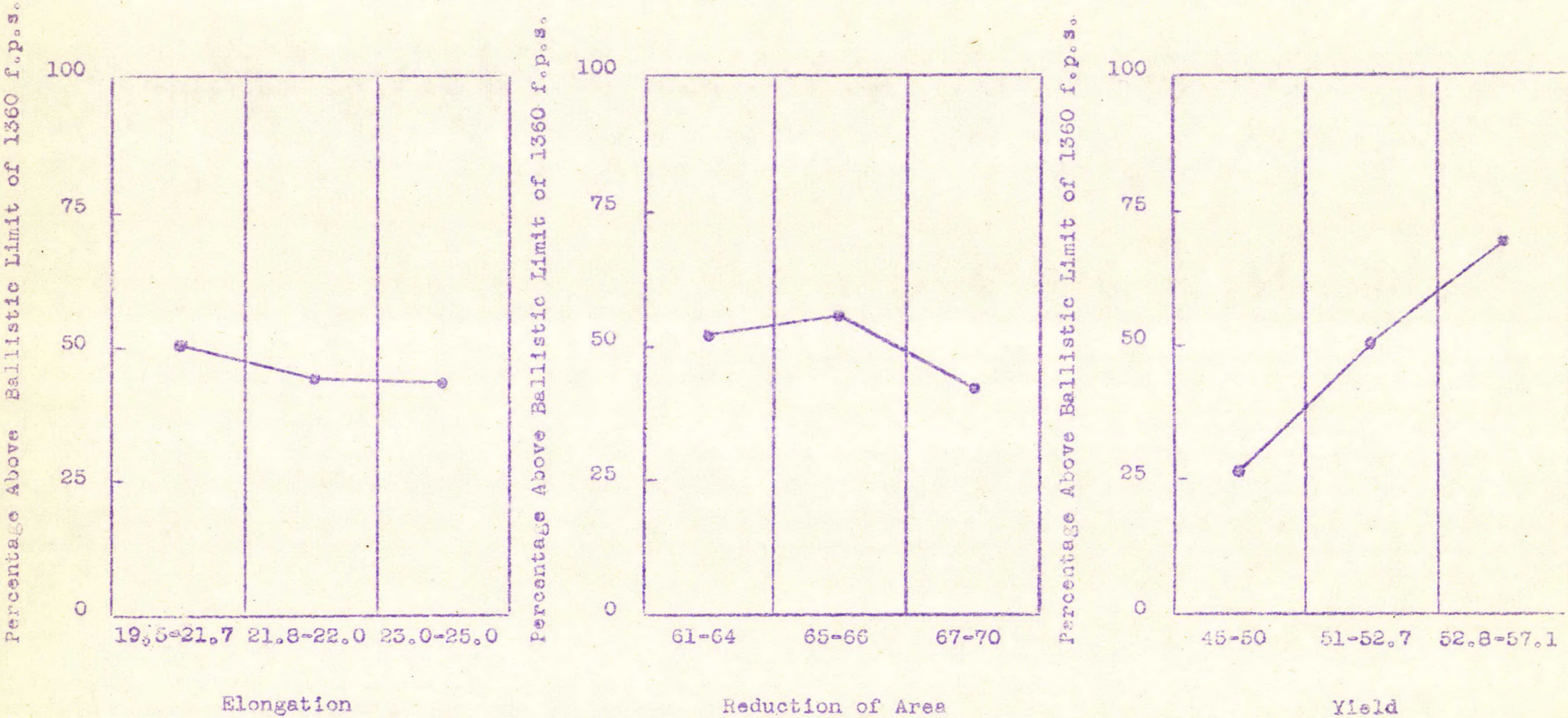
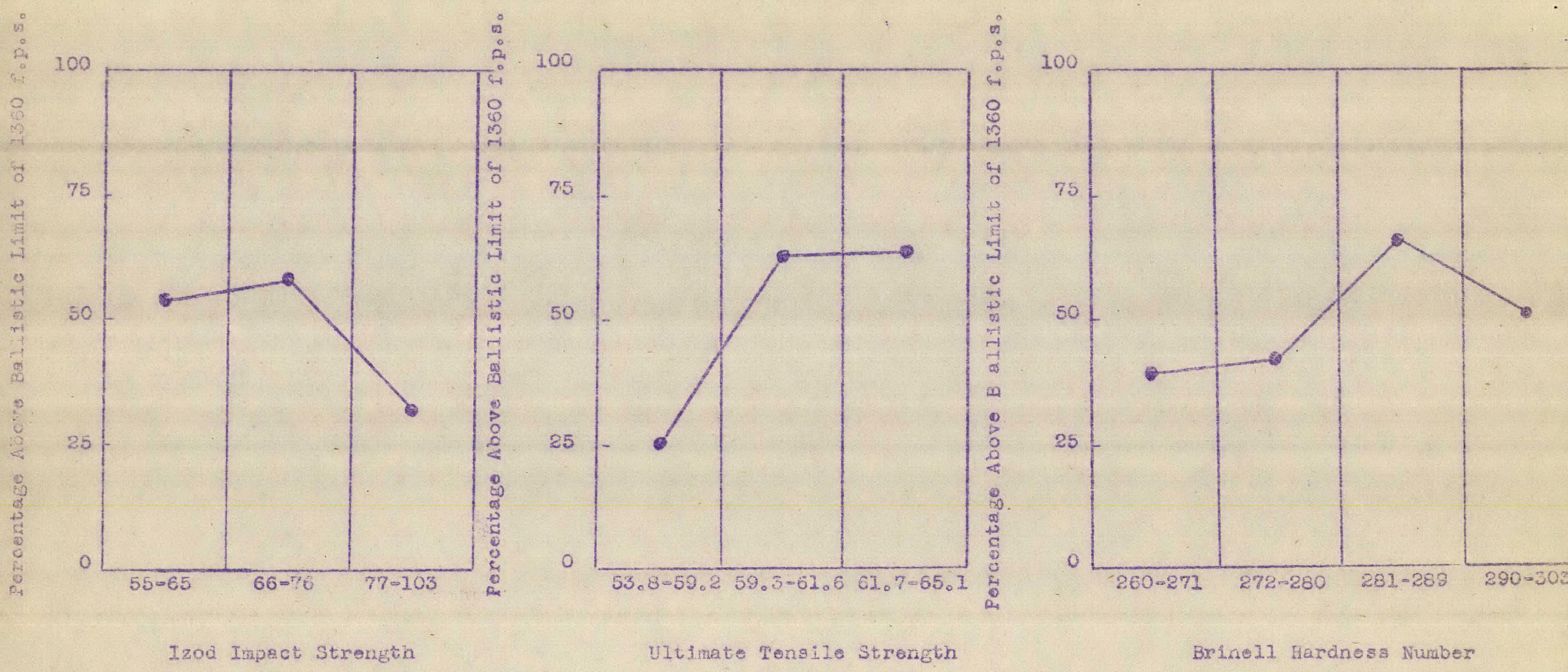


FIG 1.
EXPLANATION
20% OF BALLISTIC LIMITS WERE DETERMINED BY BRACKETING SHOTS 55 TO 59 F.P.S. APART.
FREQUENCY PER CENT
20
15
10
5
20-24
25-29
30-34
35-39
40-44
45-49
50-54
55-59
60-64
65-69
70-74
F.P.S. DIFFERENCE BETWEEN BRACKETING SHOTS USED TO DETERMINE BALLISTIC LIMIT.

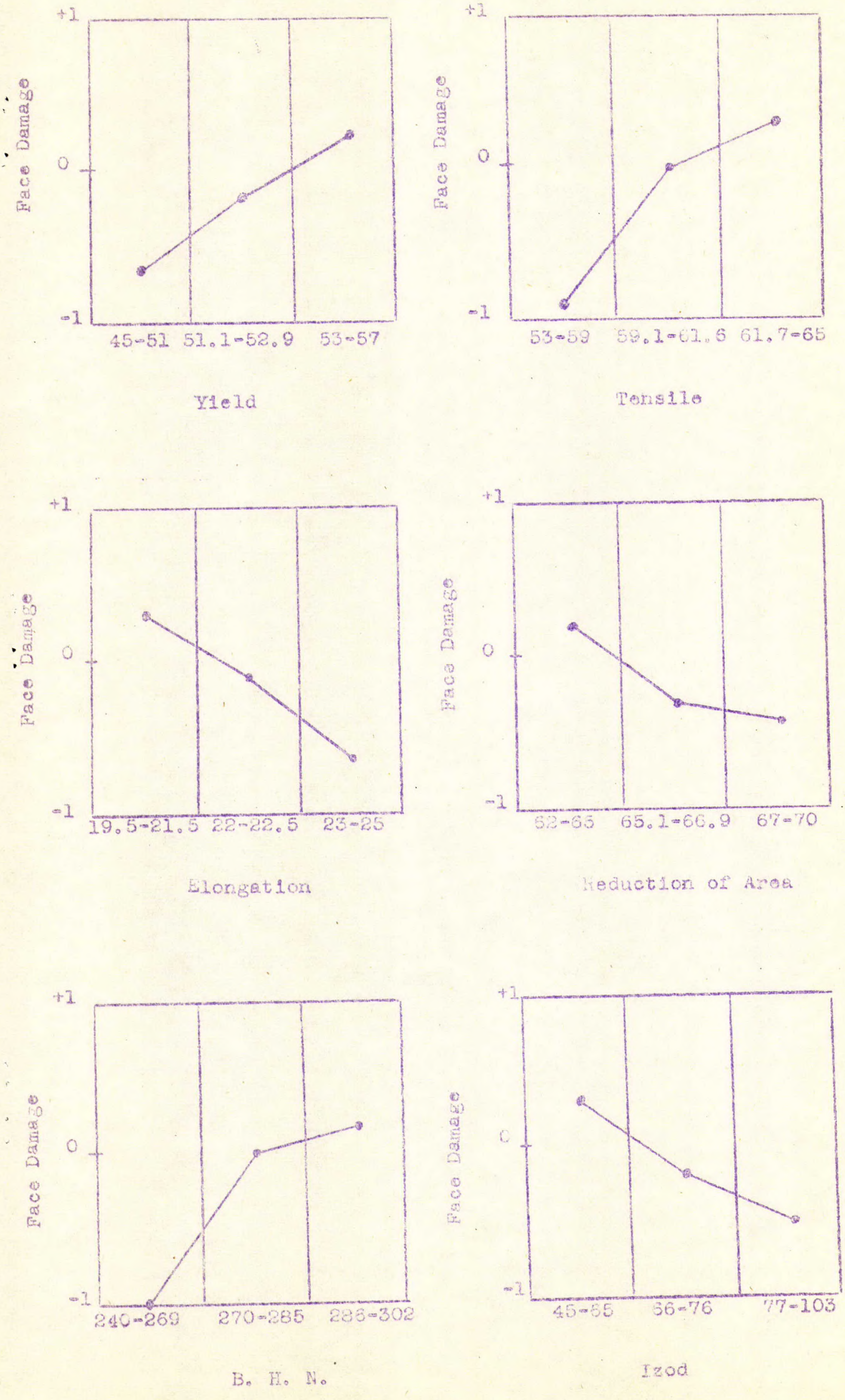
(Page 8)



(Correlation Between Ballistic Limit and Physical Tests).

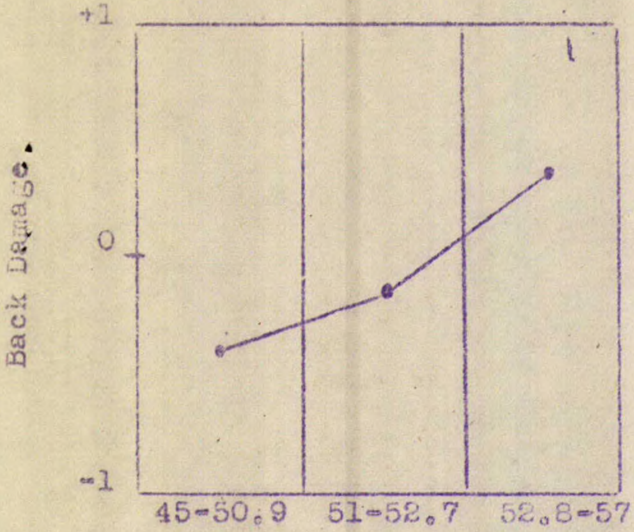


(Correlation Between Ballistic Limit and Physical Tests, cont'd).

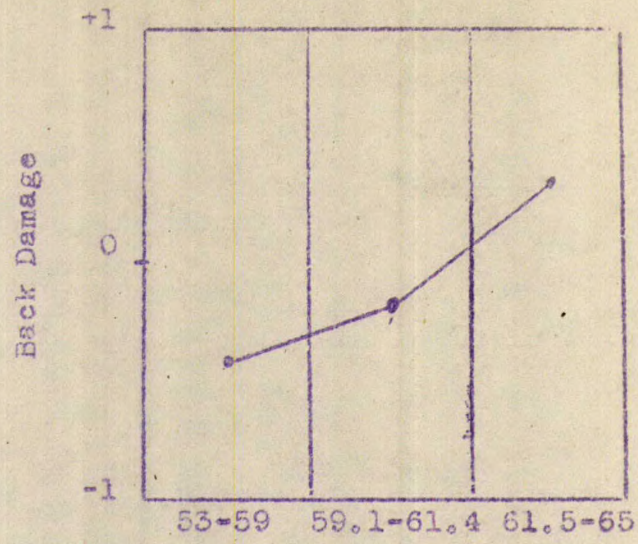


(Correlation Between Face Damage Factor and Physical Tests).

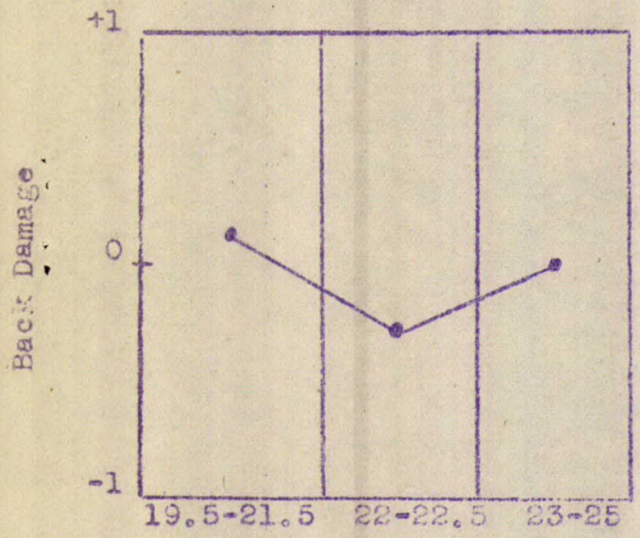
(Back Damage Correlated to Physical Properties)



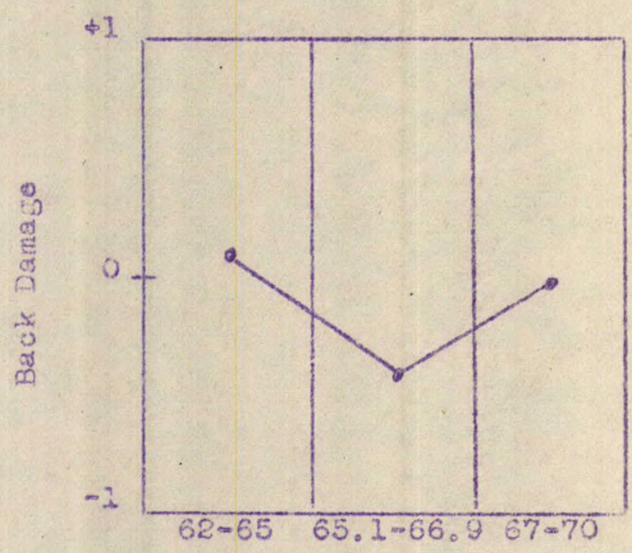
Yield



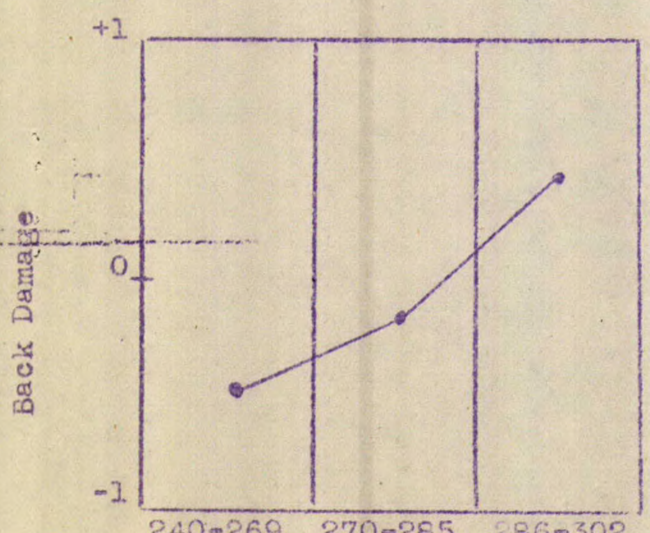
Tensile



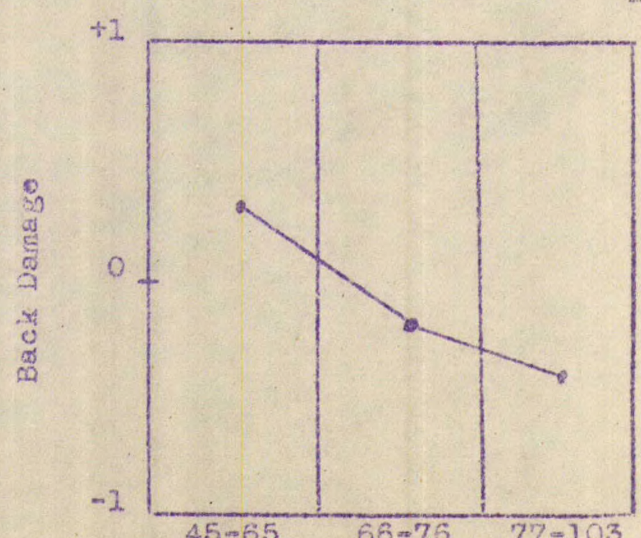
Elongation



Reduction of Area



B. H. N.



Izod

GROUPING LIST.

(Groups of 4, used in Quality Control Charts)

Group No.	Plate No.	Group No.	Plate No.
1.	R1 2 3 4	12.	R45 46 47 48
2.	R5 6 7 8	13.	R49 50 51 52
3.	R 9 10 11 12	14.	R53 54 55 56
4.	R13 14 15 16	15.	R57 58 59 60
5.	R17 18 19 20	16.	R61 62 63 64
6.	R21 22 23 24	17.	R65 66 67 68
7.	25 26 27 28	18.	R69 70 71 72
8.	R29 30 31 32	19.	R73 74 75 76
9.	R33 34 35 36	20.	R77 78 79 80
10.	R37 38 39 40	21.	R81 82 83
11.	R41 42 43 44		

HHF:GHB.