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U. S. NAVAL PROVING GROUND

DAHLGREN, VIRGINIA

REPORT NO. 7-44

EFFECT OF THE DEPTH OF FACE ON THE BALLISTIC LIMIT OF PLURAMELT LIGHT ARMOR.

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28 March 1944

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REPORT NO. 7-44

EFFECT OF THE DEPTH OF FACE ON THE BALLISTIC LIMIT OF PLURAMELT LIGHT ARMOR.

APPROVED:

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PREFACE

AUTHORIZATION

This study, authorized by Buord ltr. NP/A9 (Re3) dated 9 January, 1943, was conducted under Naval Proving Ground Experimental Department Project No. 2.

OBJECT

To determine the optimum depth of case in 3/8" and 1/2" Pluramelt face hardened light armor.

SUMMARY

A series of 3/8" and 1/2" Pluramelt plates varying in depth of face from 10% to 50% were tested with caliber .50 AP M2 bullets at normal and 20mm H.E. at 20° obliquity. Results indicate that the optimum depth of face is 28% to 40% for 1/2" plates and 20% to 30% for 3/8" plates.

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I. INTRODUCTION:

For the past three years, the Allegheny Ludlum Steel Corporation has been producing face hardened light armor by their "Pluramelt" process. This process consists of building up a metallic layer on a base metal by an electric arc. The Allegheny Ludlum Steel Corporation rolls ingots of low carbon-nickel-molybdenum steel into slabs approximately 8" thick. A 2" layer of high carbon steel of similar alloy content is melted onto the slab and the composite slab is then rolled down into the required plate gauge. The process is flexible in that it permits a variation in the composition of either the face or the back of the plate and also permits a wide variation in the ratio of face to back by varying the thickness of the slab on which the 2" layer of high carbon steel is deposited.

Previous experience of the Naval Proving Ground with 1/2" Pluramelt light armor indicated that a hard thick face supported by a fairly hard back would give the optimum resistance to penetration by Caliber .50 AP M2 bullets at 0° obliquity.(1) With 1/2" plates having approximately 40% case, limit velocities against caliber .50 AP M2 bullets of 2300 to 2400 f.s. were occasionally obtained - a margin over specifications of between 200 and 300 f.s. Many variables, such as composition of the face and back, decarburization of the face of the plate, back hardness, etc., affect the performance of Pluramelt plate and hence it was found impossible to correlate depth of case directly with ballistic performance. In order to determine the optimum depth of face for Pluramelt light armor, green plates were ordered from Allegheny Ludlum Steel Corporation in both 3/8" and 1/2" gauge. The plates were to be made from one heat, the only variable being the per cent of face.

It is understood from company representative that every effort was made by the Allegheny Ludlum Steel Corporation to have the green plates representative of standard manufacturing practice. In order to have a wide variation in face depth, ten plates of each gauge were made with 10%, 20%, 30%, 40% and 50% face, respectively.

II MATERIAL:

Four Pluramelted ingots were made, with 2" of high carbon face and a total thickness of 14" for the 20% plates, 9-3/4" for the 30% plates, 7-3/4" for the 40% plates and 6-3/4" for the 50% plates. The ingots were heated and rolled into 4" slabs 25" wide and cut to length. Two pieces were cut from the slab rolled from the 14" thick ingot. One of these slabs had 0".31 removed from the high carbon face by machining to make the 10% face plates. The slabs were then reheated and rolled into plates 1/2" and 3/8" thick by 22-1/4" wide. The plates were annealed, pickled and sheared into 36" lengths.

It it understood from company representatives that considerable difficulty was encountered in the production of the plates because of face cracking and separation - especially with the slabs having a nominal face of 40% and 50%. Out of the hundred plates ordered, comprising ten plates of each category, only 78 plates were actually delivered. No 1/2" plates having a nominal face of 50% were received.

The chemical composition of the plates is given in Table I. It will be noted that the back has 0.22% carbon while the carbon content of the face varies in the four ingots from 0.57% to 0.62%. The alloy content is practically constant for all the ingots.

TABLE I

CHEMICAL COMPOSITION OF PLURAMELT PLATES.

Back - Heat No. 53810

C	Mn	P	S	Si	Cr	Ni	Mo
.22	.50	.011	.017	.30	.13	3.39	.40

Case - 3/8" and 1/2" plates

	C	Mn	P	S	Si	Ni	Mo
10% and 20% case	.60	.56	.014	.019	.29	3.47	.43

FIG. 2

NPG PHOTO NO. 1191 (APL) - Photomicrograph of large sub-surface stringer in 1/2" Pluramelt light armor (40% Face). Left - as annealed. Right - as hardened showing soft pearlite band in tempered martensite.
25 October 1943

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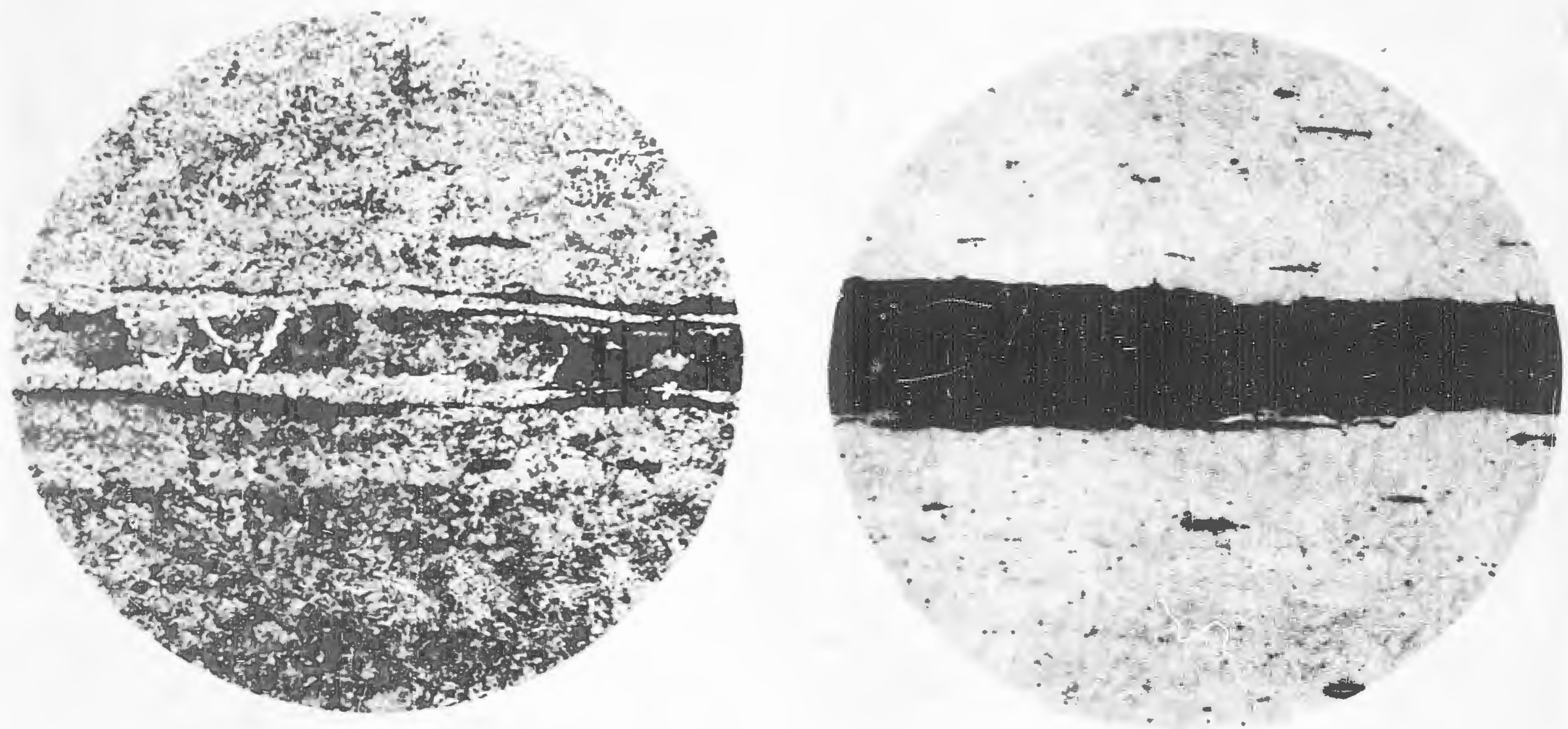

FIG. 1

NPG PHOTO NO. 1072 (APL) - Macro-etched sections from Annealed Pluramelt plates. Top row shows 1/2" plate with approximately 10, 20, 30 and 40 per cent face. Lower row shows 3/8" plate with approximately 10, 20, 30, 40 and 50 per cent face. Light area of surface of face indicates decarburization.

28 October 1943

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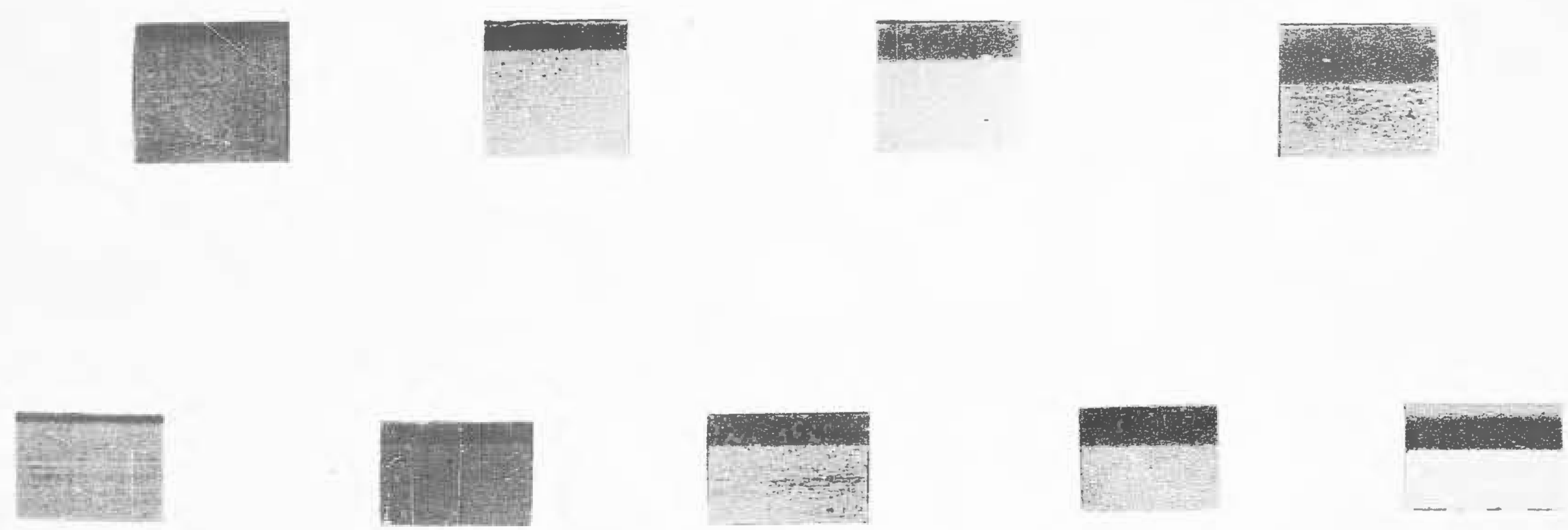

	C	Mn	P	S	Si	Ni	Mo
30% case	.57	.55	.008	.018	.27	3.41	.44
40% case	.57	.57	.011	.017	.28	3.36	.43
50% case	.62	.55	.008	.014	.28	3.38	.43

A study was made of the plates, as received, for structure, decarburization and inclusions. Samples were experimentally heat treated to determine whether a standard 1560°F. quench followed by a 300°F. draw would give a uniform tempered martensite structure. Table II gives the Brinell hardness results obtained on these samples together with results of microscopic examination. The back hardness developed by the hardening treatment was about 444 BHN, and the face hardness was above 600 BHN for all plates except for the 3/8" plates with 10% and 20% face. It was considered that the heat treatment was satisfactory since previous experience had shown the excellent penetration resistance could be obtained with plates having these hardness values.

The macro-etched sections of the annealed plates are shown in Figure I. Microscopic examination indicated that the amount of decarburization was slight except for plate G10 (3/8" - 50% face). This plate had about 0".05 partial decarburization as is evident in Figure I.

The amount of inclusions in the face was average for Pluramelt plates except for plate G4 (1/2" - 40% face) which had a bad stringer inclusion. Besides the large inclusions in this plate, the region examined was low in alloy content and did not harden on quenching in oil, which resulted in a large band of pearlite below the surface of the plate as shown in Figure 2. Such bands had previously been found in Pluramelt plates.(1) The penetration resistance of the plate does not appear to be affected by them, but the ductility under shock is decreased.

The plates were considered to be representative Pluramelt plates and therefore could be used for a study of the effect of depth of face on the penetration resistance.

III RESULTS:

Three plates from each group, 27 total, were heat treated as follows:

75 minutes in salt bath at 1560° F.
3 minutes quench in agitated oil.
1 hour draw at 300° F.

The plates were tested with caliber .50 AP M2 at normal and with 20mm H.E. at 20° obliquity under specifications O.S.2775-1. Results of ballistic tests are given in Table III.

Samples were cut from the plates and examined for depth of face, hardness and microstructure. Results are given in Table IV together with the caliber .50 AP M2 limit velocities. The limits have been corrected for variations in gauge to a standard thickness of 0".375 and 0".500 for the 3/8" and 1/2" plates respectively.

By comparing Tables II and IV, it will be seen that samples taken from the same plate had different per cents of face and that plates of the same nominal per cent face had a similar variation in the per cent of face. Since the plates of the same nominal per cent face were rolled from a single slab, it is evident that the depth of face varied in the slab. The per cent face obtained from a single location in a plate is therefore not characteristic of the plate and cannot be correlated directly with the ballistic limit.

In order to obtain a correlation between the per cent face and limit velocity, it is necessary to average the per cents of face obtained on the micro-samples and average the limit velocities obtained on plates of the same nominal per cent face. The results obtained are given in Table V and plotted in Figure 3.

NPG PHOTO NO.1190 (APL) FIG. 3 CONFIDENTIAL

VARIATION OF VELOCITY LIMIT WITH PERCENT FACE
FOR 3/8" AND 1/2" PLURAMELT PLATES
(Back Hardness Approximately 444 BHN)
(Cal. .50 AP M2 Bullets At 0° Obliquity)

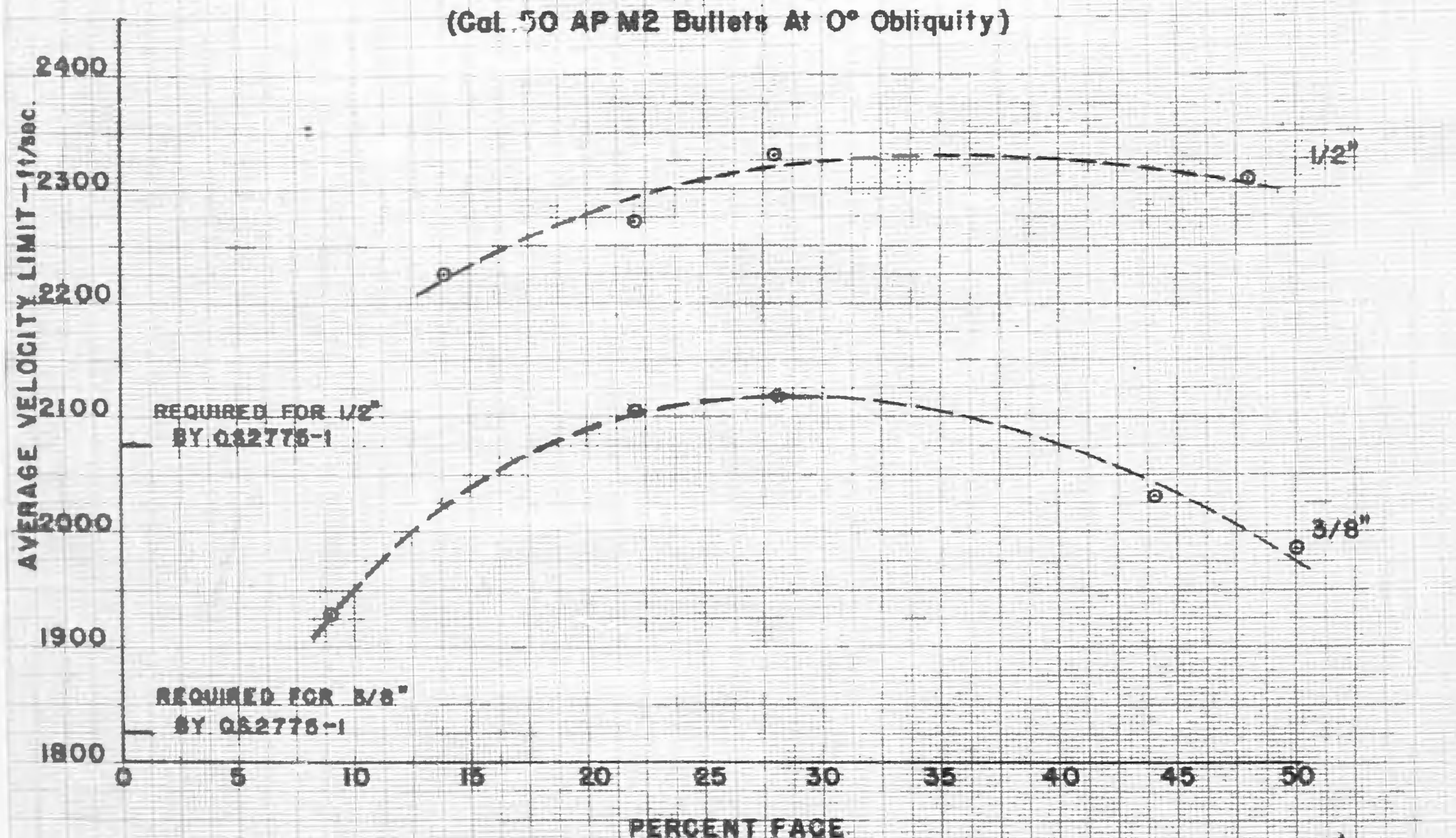

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TABLE V

AVERAGE VELOCITY LIMIT IN FT./SEC. OF PLURAMELT PLATES OF VARYING PER CENT FACE vs. CAL. .50 AP M2 BULLETS AT NORMAL.

3/8" % Face	3/8" Limit	1/2" % Face	1/2" Limit
9	1927	14	2226
22	2102	22	2268
28	2116	28	2329
44	2032	48	2307
50	1984		

IV DISCUSSION:

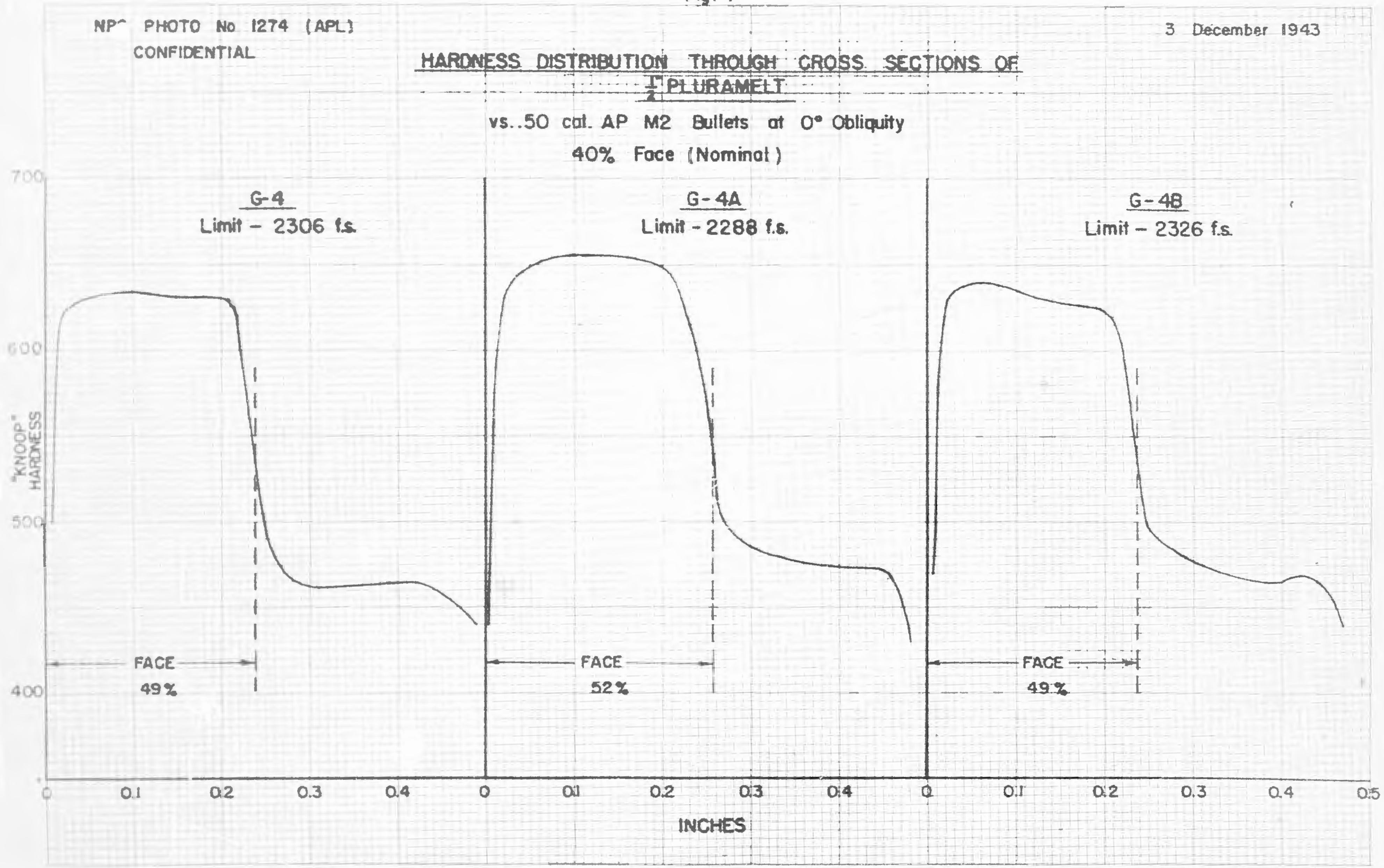
1/2" Plates

From the curves in Figure 3, it would appear that the optimum depth of face for penetration resistance of 1/2" plates vs. caliber .50 AP M2 bullets at normal is above 28% and is probably about 35%. Unfortunately, no plates were furnished with a depth of face between 28% and 48%. This gap is in the range that is most important for 1/2" Pluramelt face hardened armor.

The curve has been dotted to indicate a lack of certainty in the shape of the curve and in the location of the maximum. In fact, there is some evidence that the curve is not a continuous function. The plates with a large per cent of face failed with large buttons being thrown from the back of the plate instead of failing with clean punchings as is usual for plates of lower per cent face. The change in the mechanism of plate failure probably causes an abrupt break in limit velocity. Variations in plate composition, back hardness and heat treatment will affect the per cent of face for optimum ballistic properties.

An interesting feature of the results was that the limits obtained on all the plates regardless of depth of face were so high. Even the plates with 14% face had an average limit 150 ft./sec. over specification requirements for 1/2" plates while the average limits of all plates between 23% face and 50% face was above 2300 ft./sec.

Fig. 7


NP^ PHOTO No. 1274 (APL)
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3 December 1943
HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF
1" PLURAMELT
vs. .50 cal. AP M2 Bullets at 0° Obliquity
40% Face (Nominal)
G-4
Limit - 2306 f.s.
G-4A
Limit - 2288 f.s.
G-4B
Limit - 2326 f.s.
FACE
49%
FACE
52%
FACE
49%
"KNOOP" HARDNESS
700
600
500
400
0
0.1
0.2
0.3
0.4
0
0.1
0.2
0.3
0.4
0
0.1
0.2
0.3
0.4
0.5
INCHES

Fig. 4

NPG PHOTO No 1271 (APL)
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3 December 1943

HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF
$\frac{1}{2}$" PLURAMELT
vs. .50 cal AP M2 Bullets at 0° Obliquity
10% Face (Nominal)

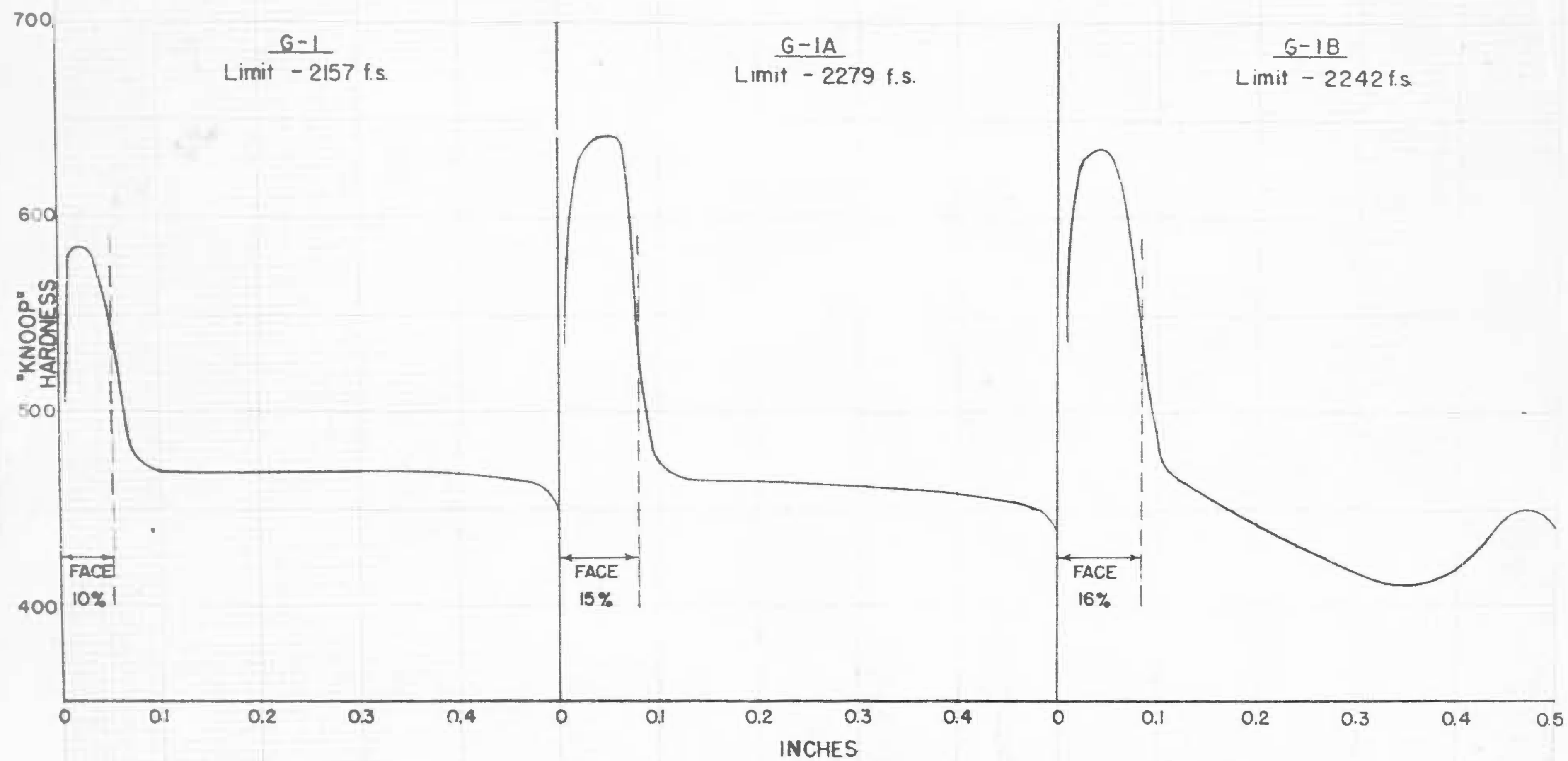
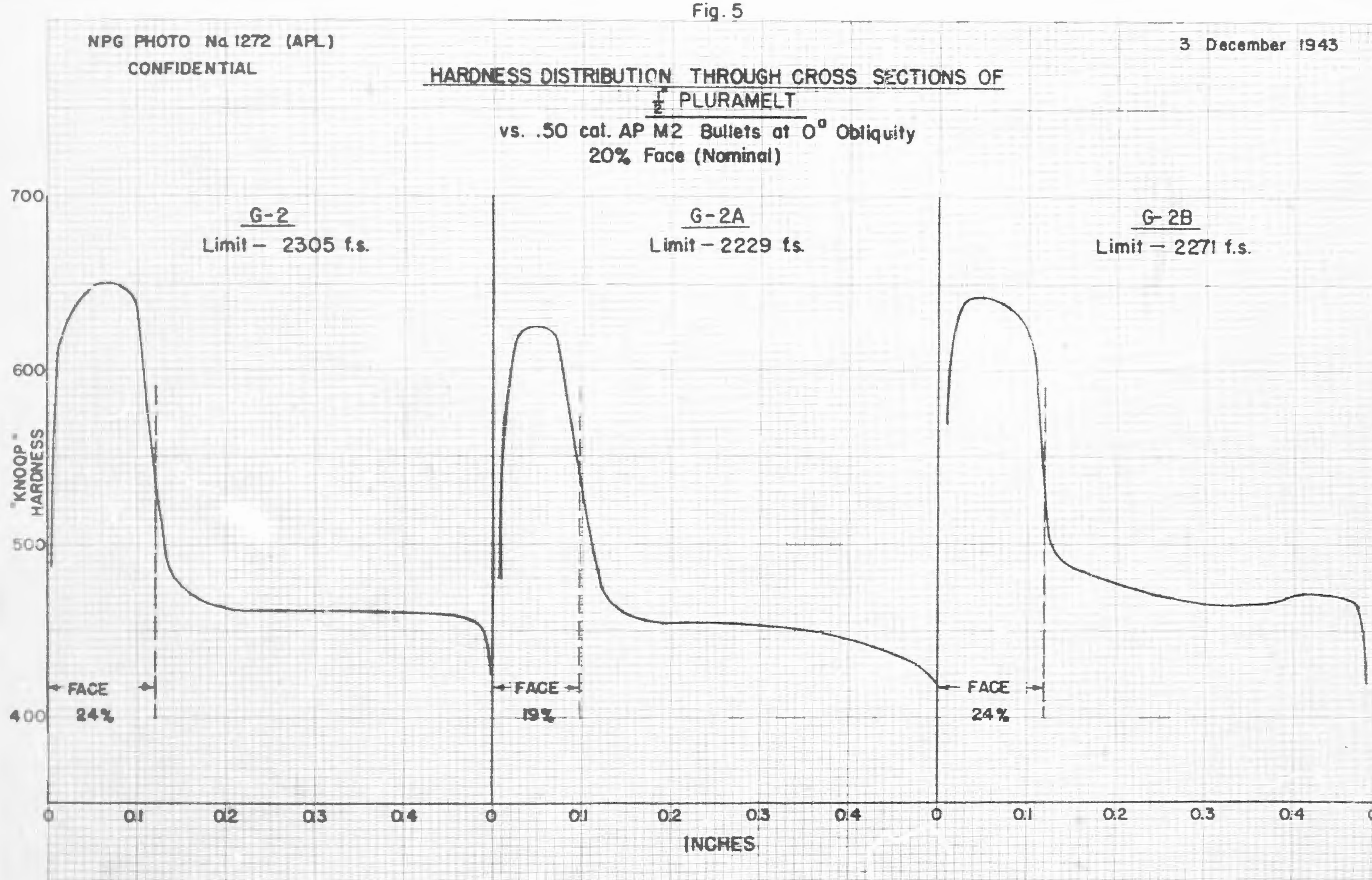


Fig. 5


NPG PHOTO No. 1272 (APL)
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3 December 1943
HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF
½" PLURAMELT
vs. .50 cal. AP M2 Bullets at 0° Obliquity
20% Face (Nominal)
G-2
Limit - 2305 f.s.
G-2A
Limit - 2229 f.s.
G-2B
Limit - 2271 f.s.
"KNOOP" HARDNESS
700
600
500
400
FACE
24%
FACE
19%
FACE
24%
0
0.1
0.2
0.3
0.4
0.5
INCHES

Fig. 6

NPG PHOTO No. 1273 (APL)

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HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF 1/2" PLURAMELT

vs. .50 cal. AP M2 Bullets at 0° Obliquity
30% Face (Norminal)

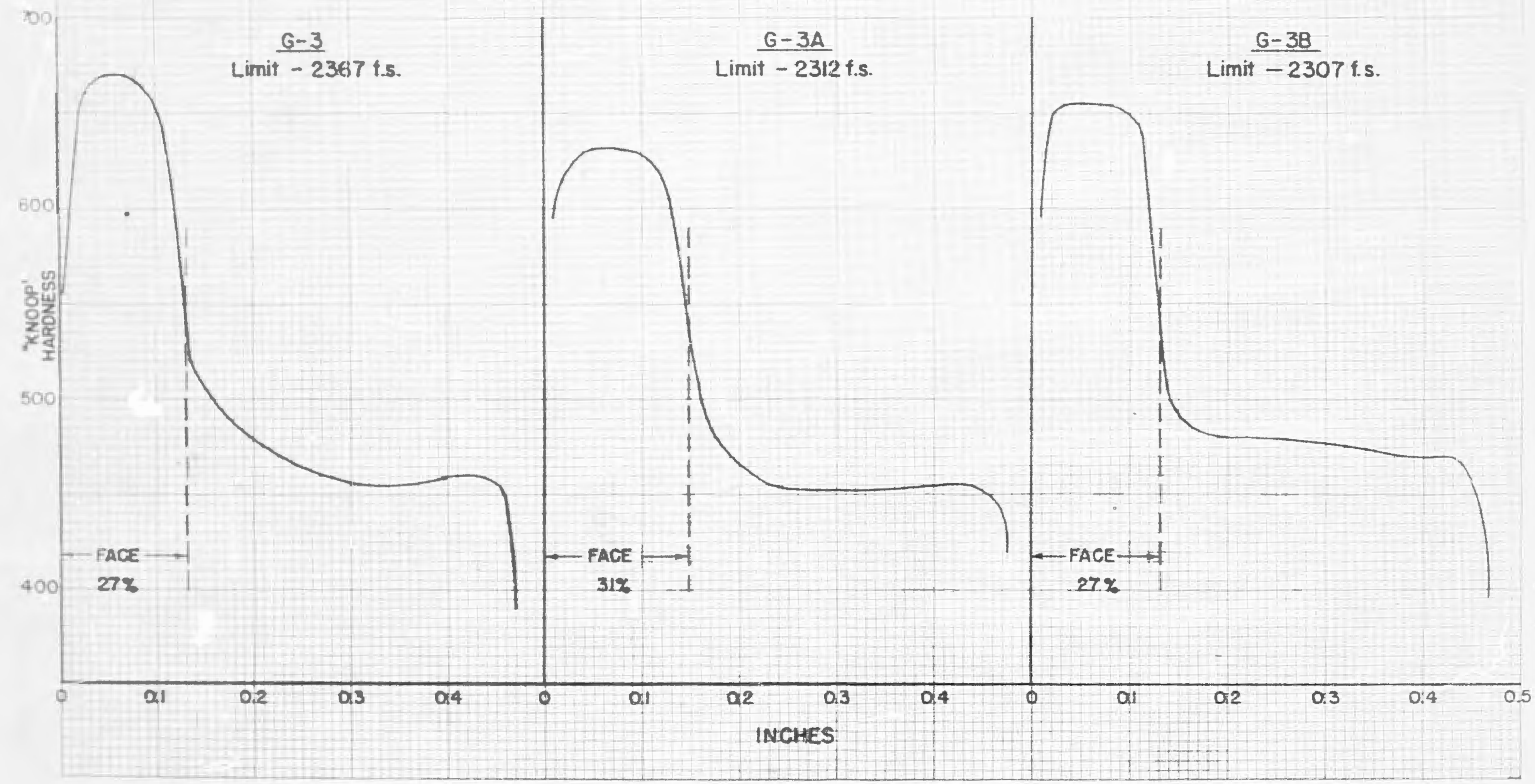
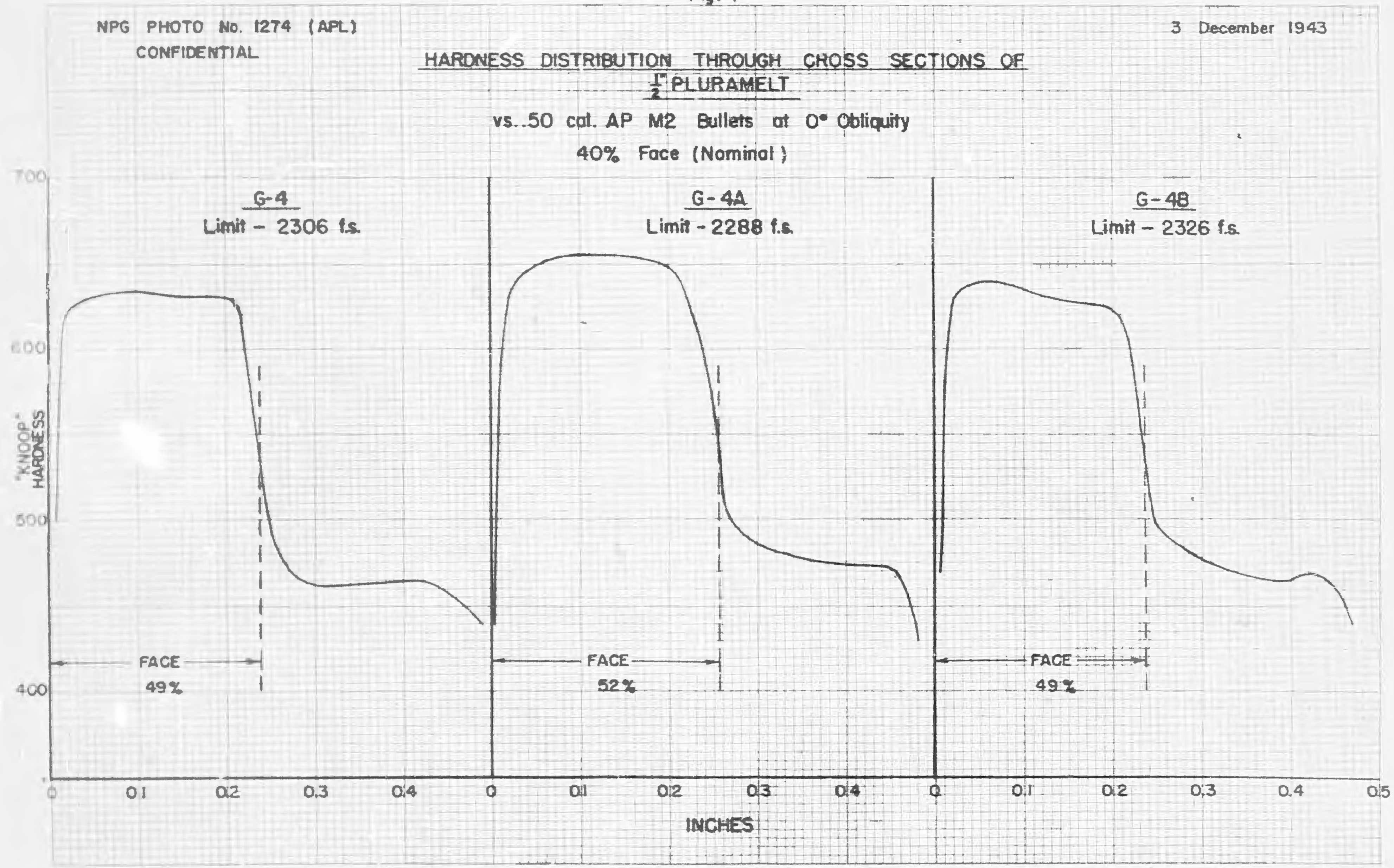


Fig. 7


NPG PHOTO No. 1274 (APL)
CONFIDENTIAL
3 December 1943
HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF
1/2" PLURAMELT
vs. .50 cal. AP M2 Bullets at 0° Obliquity
40% Face (Nominal)
G-4
Limit - 2306 f.s.
G-4A
Limit - 2288 f.s.
G-4B
Limit - 2326 f.s.
FACE
49%
FACE
52%
FACE
49%
"KNOOP" HARDNESS
700
600
500
400
0
0.1
0.2
0.3
0.4
0
0.1
0.2
0.3
0.4
0
0.1
0.2
0.3
0.4
0.5
INCHES

All the 1/2" plates passed the shock test with the 20mm H.E. ammunition at 20° obliquity except plate G4 which failed by giving a 4-1/2" by 1-1/2" face spall. The face spall was caused by the large pearlite bands found in the face (Figure 2). It should be noted that this plate with 48% face had a limit of 2306 ft./sec. in spite of the large subsurface defect.

Since these plates had high ballistic limits, it was of interest to obtain complete hardness distribution curves through the plates. The hardness readings were taken with a "Tukon" machine equipped with a "Knoop" indenter. The curves for the twelve 1/2" plates are shown in Figures 4 to 7. It will be seen that all plates had a maximum hardness of over 600 Knoop except plate G1, a plate which had a ballistic limit of only 2157 ft./sec.

In Naval Proving Ground Report 12-43, (2) it was stated that 1/2" plates would probably fail the ballistic test against caliber .50 AP M2 projectiles at normal obliquity if the Knoop hardness was less than 540 at a depth of .010" because the penetration resistance of face-hardened light armor is primarily dependent on the ability of the plate to fracture the core of the AP projectile. If considerable decarburization is present on the surface of the plate, the projectile is not shattered on impact and passes through the plate substantially undeformed. The hardness of the twelve 1/2" plates shown in Figures 4 to 7 is well above 540 Knoop at ".010 below the surface of the face. However, the plates all show a marked drop off in hardness at the surface which is believed to lower the ballistic limits, and is also probably one factor responsible for the wide variation in ballistic limits found in Pluramelt armor. It is believed that more care should be taken to minimize this sharp drop in hardness at the surface of face hardened armor.

<u>3/8" Plates</u>

From the curves in Figure 3, it would appear that the optimum depth of case for penetration resistance of 3/8" plates against caliber .50 AP M2 bullets at normal is between 20% and 30% face. As in the case of the 1/2" plates, there is a large gap in the per cent face in this range. Since there are no plates with per cent face in the range from 28% to 44% it is impossible to fix the optimum depth of face with certainty. As in

Fig 8

HARDNESS DISTRIBUTION THROUGH CROSS SECTION OF
3/4" PLURAMELT
vs. .50 cal. AP M2 Bullets at 0° Obliquity
10% Face (Nominal)

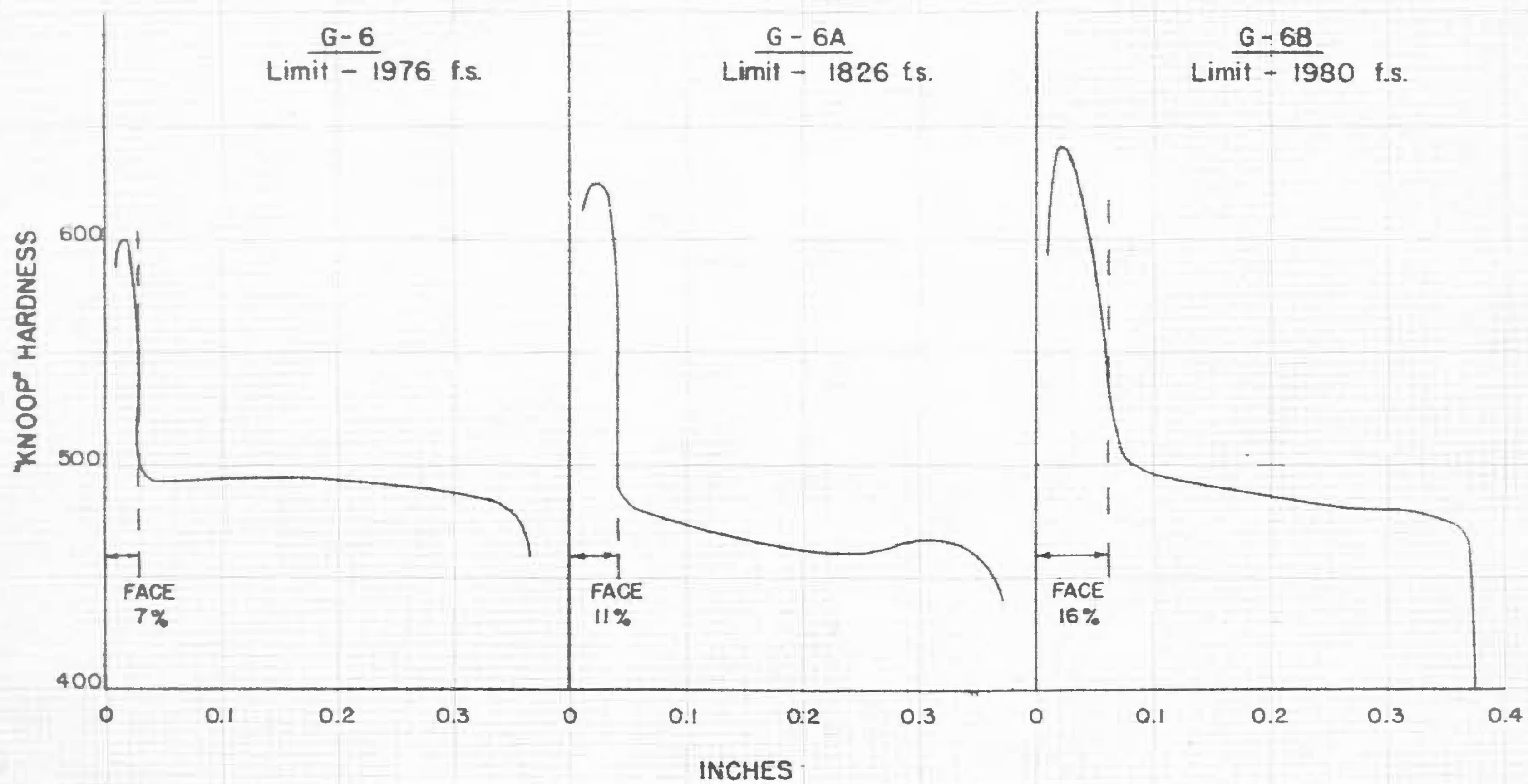


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Fig. 9

HARDNESS DISTRIBUTION THROUGH CROSS SECTION OF
$\frac{3}{8}$" PLURAMELT
vs. .50 cal. AP M2 Bullets at 0° Obliquity
20% Face (Nominal)

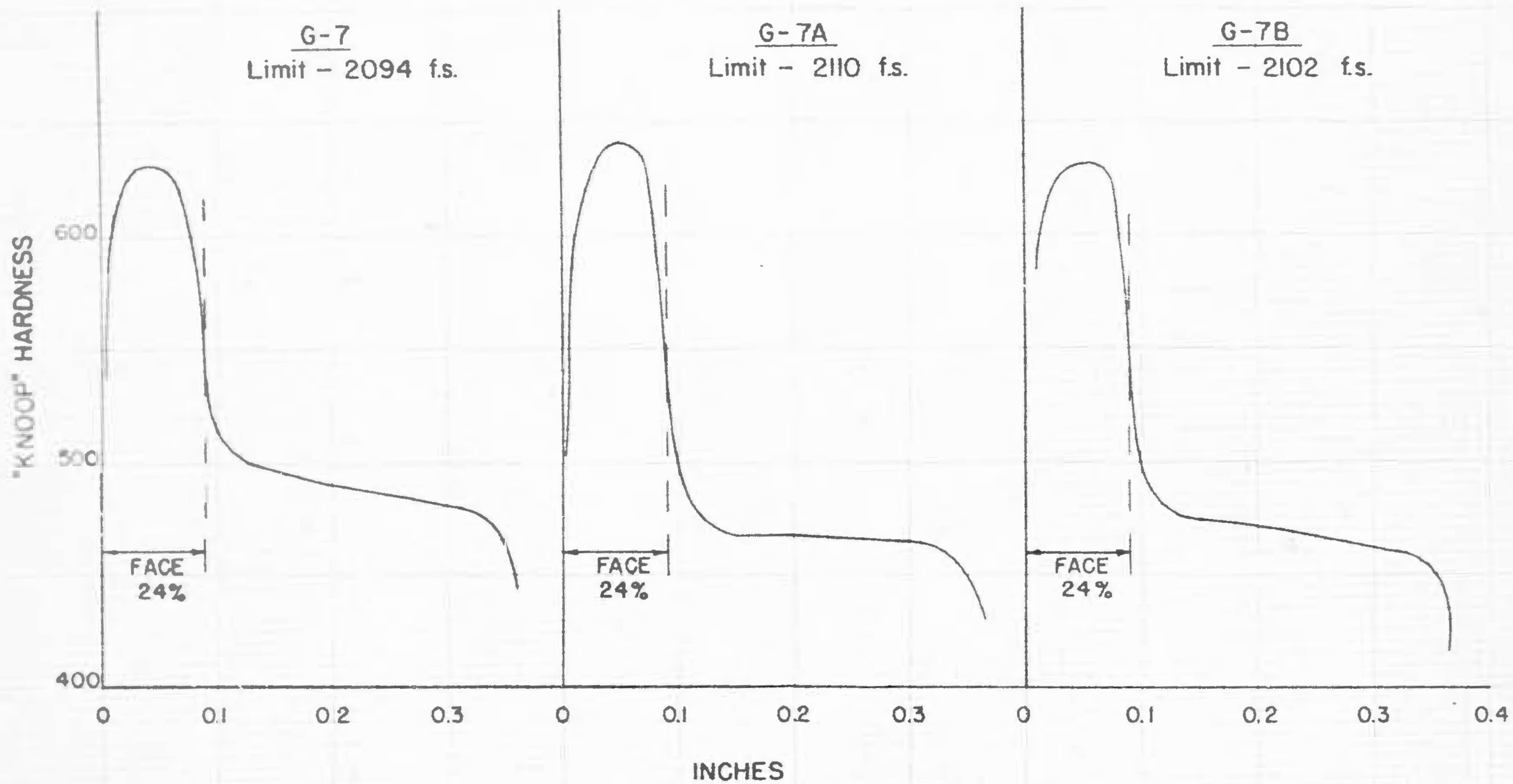

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Fig. 8

HARDNESS DISTRIBUTION THROUGH CROSS SECTION OF $\frac{3}{8}$" PLURAMELT

vs. .50 cal. AP M2 Bullets at 0° Obliquity

10% Face (Nominal)

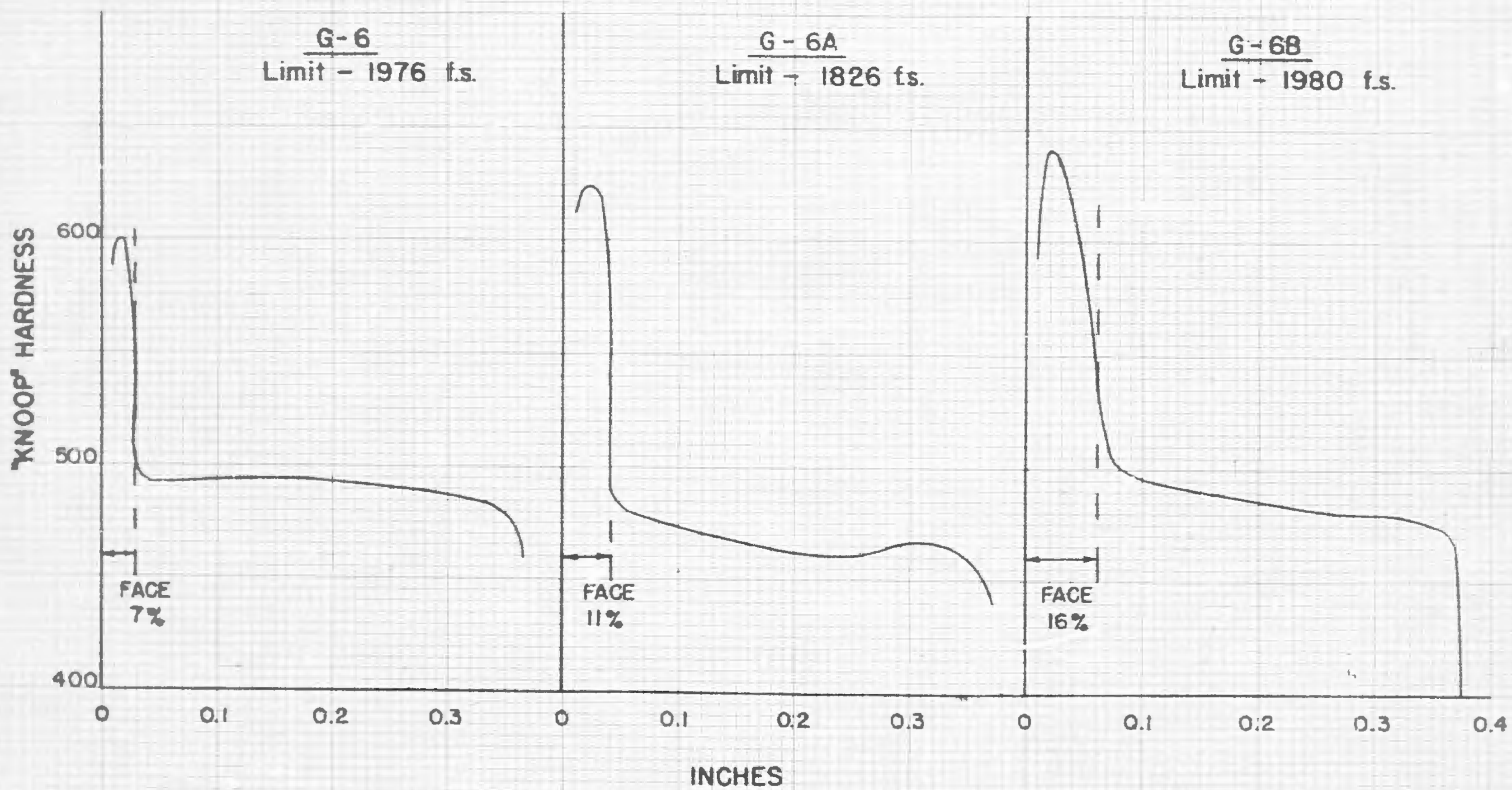

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Fig. 9

HARDNESS DISTRIBUTION THROUGH CROSS SECTION OF 3/8" PLURAMELT

vs. .50 cal. AP M2 Bullets at 0° Obliquity

20% Face (Nominal)

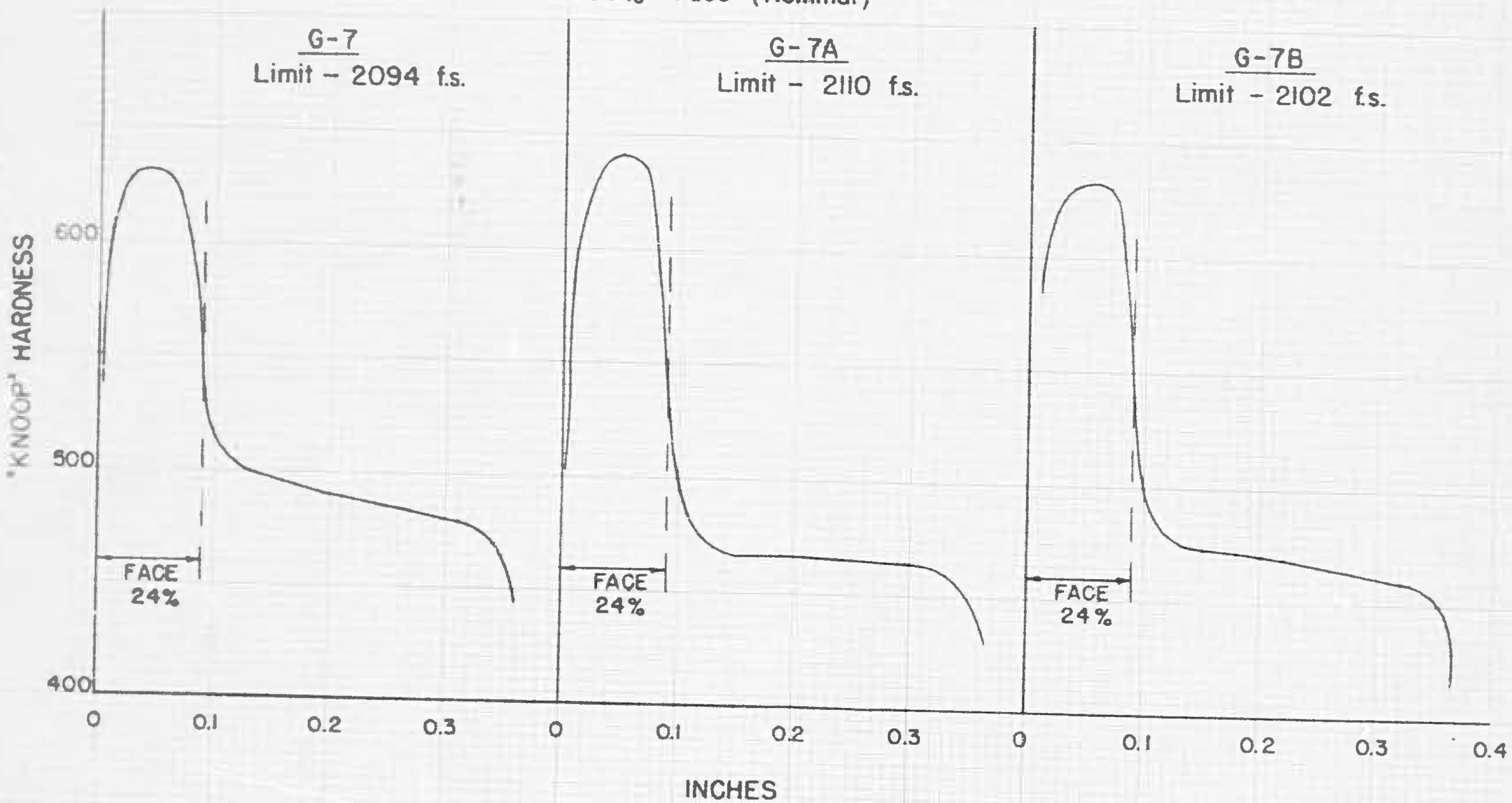

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Fig. 10

HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF $\frac{3}{8}$" PLURAMELT

vs. .50 cal AP M2 Bullets at 0° Obliquity
30% Face (Nominal)

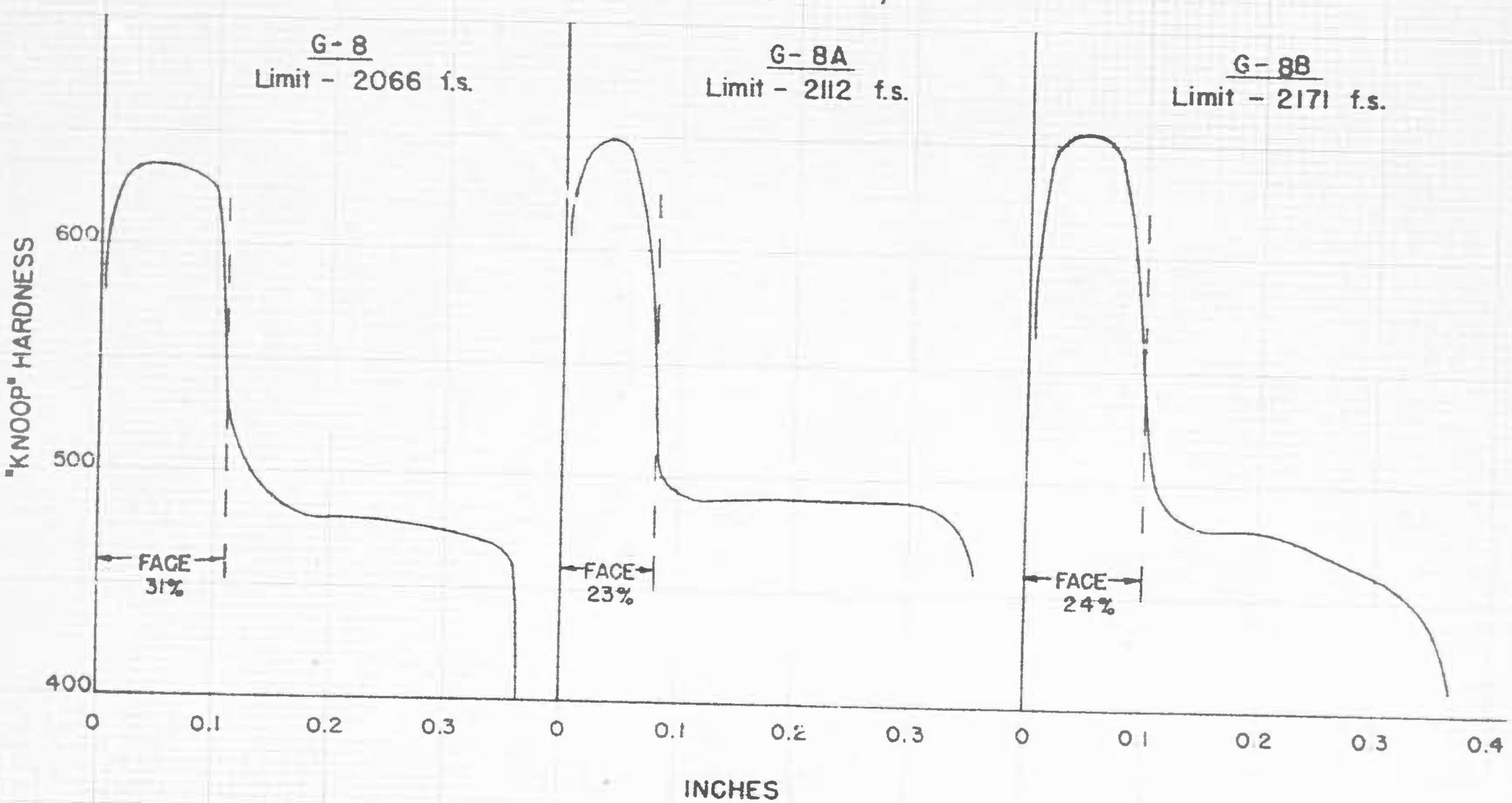

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Fig. 11

HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF $\frac{3}{8}$" PLURAMELT

vs. .50 cal. AP M2 Bullets at 0° Obliquity
40% Face (Nominal)

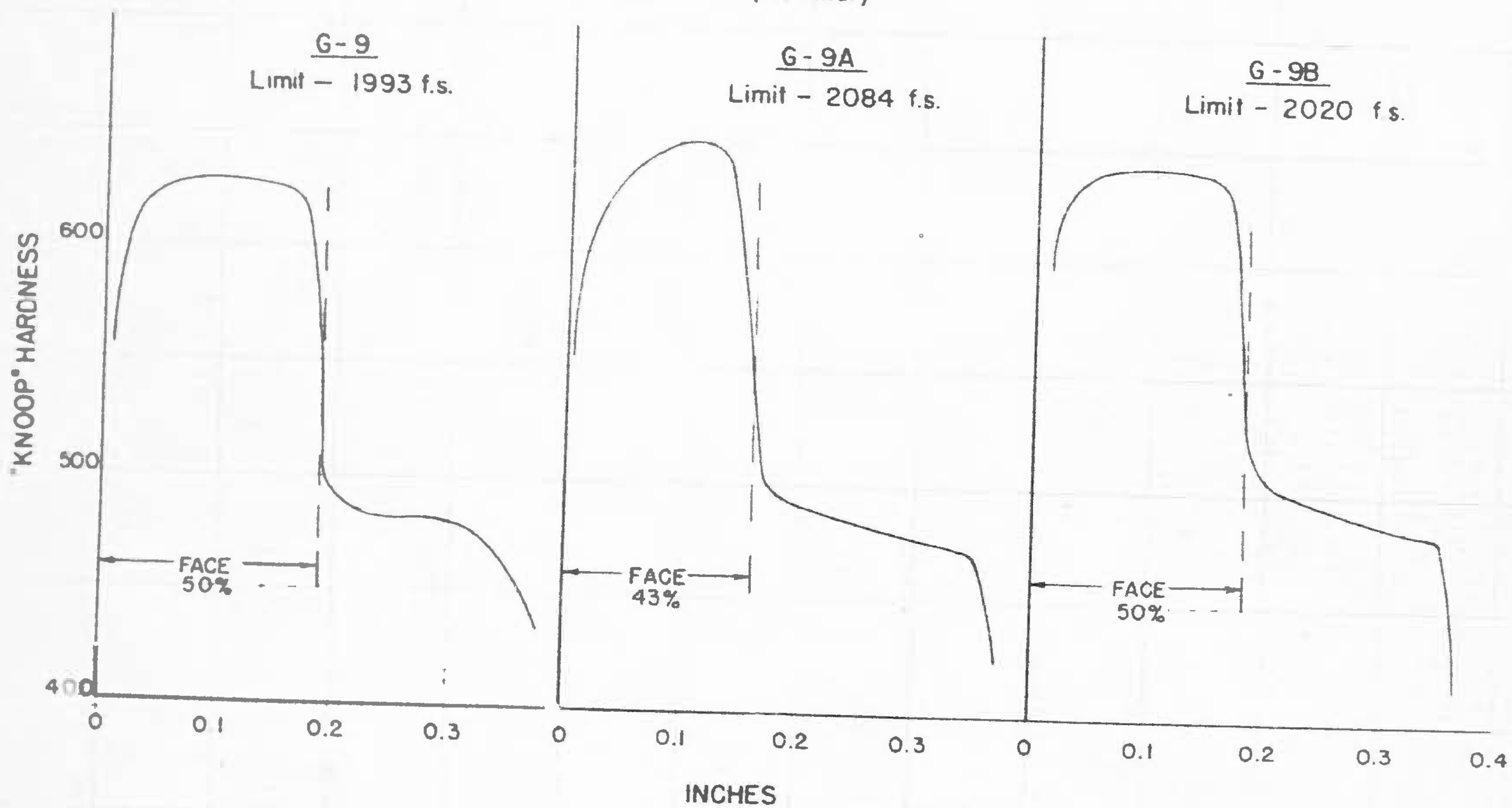

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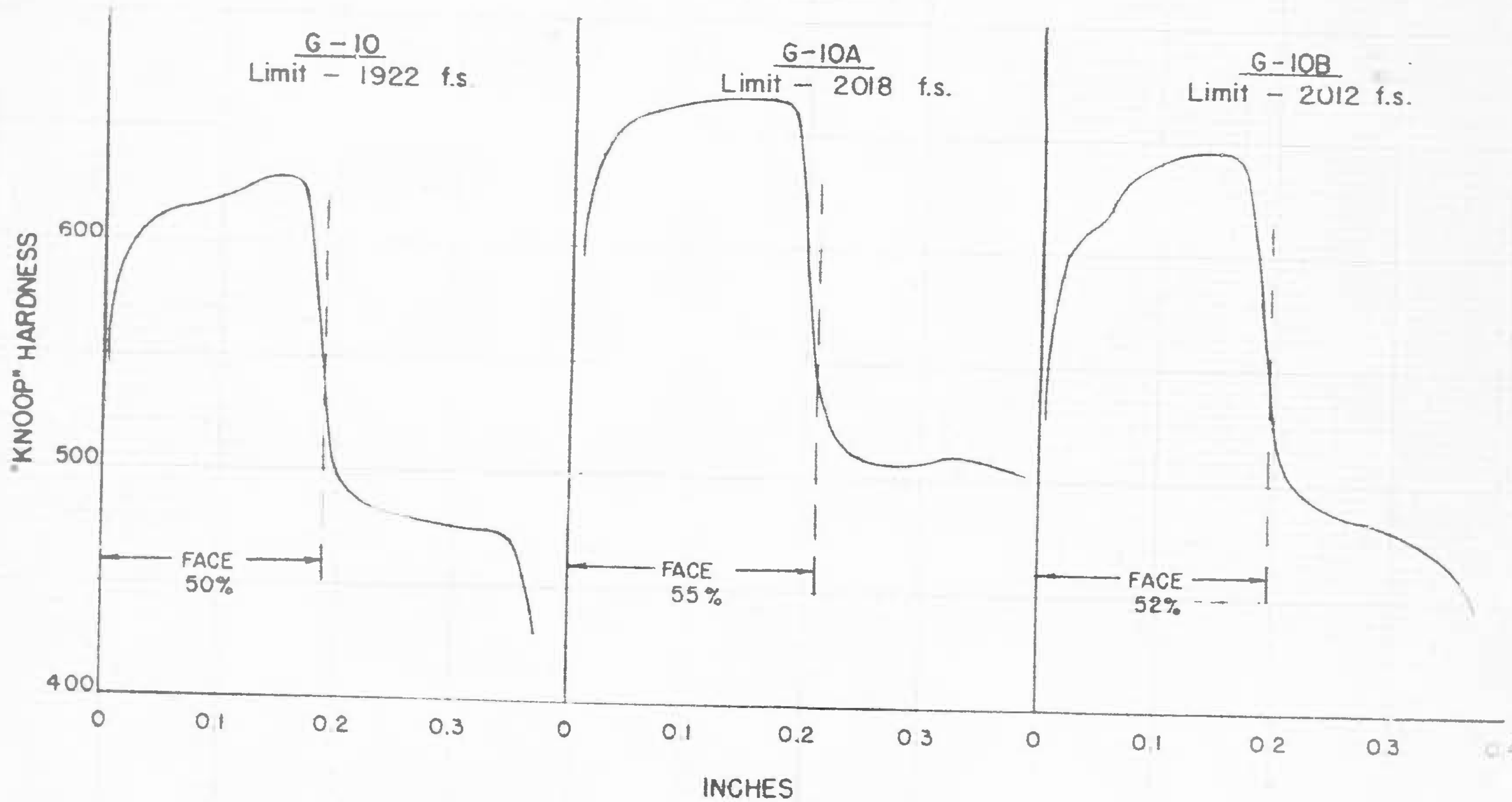
Fig. 12

HARDNESS DISTRIBUTION THROUGH CROSS SECTIONS OF
$\frac{3}{8}$" PLURAMELT

vs. 50 cal. AP M2 Bullets at 0° Obliquity
50% Face (Nominal)



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the case of 1/2" plates, however, all 3/8" plates had limits above specification requirements - even the plate with 9% - while the average limits of the plates with 20% to 30% face were above the requirements for 1/2" plates.

Only the plates with 22% face passed both the caliber .50 burst and 20mm H.E. shock tests. The plates with 44% and 50% case were definitely over the optimum depth of face since large buttons were thrown in all cases. Plates G6A and G8A failed on account of face spalls which were probably caused by pearlite bands in the face. Plate G8B with 28% face failed the 20mm shock test. No cause could be seen for the failure of this plate except that the back hardness of the 3/8" plates may be too high for this gauge. The back hardness of all 3/8" plates was above 450 Knoop and even above 500 in the case of plate 10A (See Figures 8 to 12). It would seem that for optimum ballistic properties of 3/8" face hardened armor against caliber .50 AP M2 bullets or 20mm H.E., the depth of face and the back hardness should both be less than for 1/2" plates against the same projectiles.

The per cent face given on the hardness distribution curves were taken arbitrarily at the point where the hardness falls to 540 Knoop, which corresponds to approximately 500 Brinell. The values obtained from the curves check within 2% for the 1/2" plates and within 4% for the 3/8" plates with those obtained microscopially. No significant change in the optimum depth of face would result from using the per cent face obtained from the hardness curves.

V CONCLUSIONS:

From the results obtained the optimum depth of face of 1/2" Pluramelt face hardened armor against caliber .50 AP M2 bullets would appear to be between 28% and 40% face, confirming the results given in Naval Proving Ground Report 3-43.[1] It is considered possible that 1/2" Pluramelt face hardened armor with the following characteristics would have limits consistently above 2275 ft./sec., - a margin of 200 ft./sec. over present specification requirements.

% Carbon	Face 0.57 to 0.62 Back 0.22 to 0.24
Hardness	Face over 600 BHN Back 444 BHN
% Face	30% to 40%

The optimum depth of case for 3/8" Pluramelt face hardened armor is between 20% and 30%. To obtain maximum shock resistance the back hardness should probably be lower than that for 1/2" plates which would mean a slightly lower carbon content in the back. It is believed that 3/8" Pluramelt face hardened armor with the following characteristics would have limits consistently above 2025 ft./sec. - a margin of 200 ft./sec. over present specification requirements.

% Carbon	Face 0.57 to 0.62 Back 0.20 to 0.22
Hardness	Face - Over 600 BHN Back - 400 BHN
% Face	20% to 30%

VI REFERENCES:

(1) NPG Report No. 3-43 of 2 March, 1943.
(2) NPG Report No. 12-43 of 30 June, 1943.

TABLE II

[illegible]

Sample	Gauge	Nominal	Actual % Red.	Face	Back	Annealed Microstructure
G1	1/2"	10	16	601	444	".004 Partial decarburization
G2	1/2"	20	23	[illegible]	444	".005 Partial decarburization
G3	1/2"	30	29	632	450	".004 Partial decarburization
G4	1/2"	40	44	605	444	".007 Partial decarburization Bad stringer in face.
G6	3/8"	[illegible]	[illegible]	[illegible]	[illegible]	".005 Partial decarburization
G7	3/8"	20	25	[illegible]	450	".013 Partial decarburization
G8	3/8"	30	31	[illegible]	450	".0[illegible]3 Partial decarburization.
G9	3/8"	40	42	[illegible]	444	".010 Partial decarburization
G10	3/8"	50	47	[illegible]	453	".050 Partial decarburization

TABLE III

RESULTS OF BALLISTICS OF PLURAMENT PLATES.

Plate No.	Gauge	% Face (Nominal)	Cal. .50 AP M2 Vel. Limit	Corr. Limit to STD Thick.	20mm HE Limit 20° Obliquity	Results under OS 2775-1
G1	0.518	10%	2172	2157	2781	Passed.
G1A	0.512	10%	2289	2279	2737	Passed.
G1B	0.503	10%	2244	2242	2746	Passed.
G2	0.503	20%	2307	2305	2787	Passed.
G2A	0.519	20%	2246	2229	2795	Passed.
G2B	0.499	20%	2270	2271	2806	Passed.
G3	0.489	30%	2358	2367	2776	Passed.
G3A	0.486	30%	2300	2312	2759	Passed.
G3B	0.484	30%	2294	2307	2776	Passed.
G4	0.494	40%	2301	2306	2744	Failed on 20mm on account of 4-1/2 x 1-1/2" face spall.
G4A	0.489	40%	2279	2288	2754	Passed.
G4B	0.496	40%	2323	2326	2773	Passed.
G6	0.385	10%	2005	1976	2694	Passed.
G6A	0.380	10%	1841	1826	2645	Failed-.50 Cal. (Face separation)
G6B	0.387	10%	2015	1980	2676	Passed.

TABLE III (Cont'd.)

Plate No.	Gauge	% Face (Nominal)	Cal. 150 AP M2 Vel. Limit	Corr. Limit to STD Thick.	20mm HE Limit 20° Obliquity	Results under OS 2775-1
G7	0.373	20%	20[illegible]	2094	2645	Passed.
G7A	0.377	20%	2116	2110	2720	Passed.
G7B	0.379	20%	2114	2102	2627	Passed.
G8	0.369	30%	2049	2066	2575	Passed.
G8A	0.381	30%	2129	2112	2691	Failed-.50 Cal. (Face spall)
G8B	0.372	30%	2162	2171	2475	Failed-20mm shock.
G9	0.376	40%	1996	1993	2627	Failed-.50 Cal. (2" button)
G9A	0.377	40%	2090	2094	2700	Failed-.50 Cal. (1-3/4" button)
G9B	0.373	40%	2014	2020	2600	Failed-.50 Cal. (1-3/4" button)
G10	0.388	50%	1960	1922	2497	Failed-.50 Cal. 1-3/4" and 20mm shock button)
G10A	0.386	50%	2050	2018	2572	Failed-.50 Cal. (1-3/4" and 20mm shock button)
G10B	0.390	50%	2060	2012	2623	Failed-.50 Cal. (1-3/4" and 20mm shock button)

* Velocity Limit corrected for variations in gauge.

TABLE 17

DEPTH OF FACE, BRINELL HARDNESS, AND MICROSTRUCTURE OF PLURAMELT PLATES

Plate No.	Cal. .50 Limited Correlated to St'd. Thickness.	% Face	Brinell Hardness Face	Brinell Hardness Back	Microstructure
G1	2157	10	578	430	Trace of austenite in case - Martensitic Back.
G1A	2279	15	600	43[illegible]	Trace of austenite in case- Martensitic Back.
G1B	2242	16	600	437	Trace of austenite in case - Martensitic Back.
G2	2305	23	640	444	Pearlite band in case - some ferrite in back.
G2A	2229	20	[illegible]	433	Trace of austenite in case - Martensitic Back.
G2B	2271	22	[illegible]	433	Tracer of austenite in case - Martensitic Back.
G3	2367	27	600	435	Trace of austenite in case - Martensitic Back.
G3A	2312	29	[illegible]	444	Some ferrite in back.
[illegible]	2307	27	622	437	Trace of austenite in case - Martensitic Back
G4	2306	47	600	441	Large pearlite band in case.
G4A	2288	50	605	444	Large pearlite band in case.
G4B	2326	48	[illegible]	437	Trace of austenite in case - [illegible] back

TABLE IV (Cont'd.)

Plate No.	Cal. .50 Limited corrected to Std. Thickness	% Face	Brinell Hardness Face	Brinell Hardness Back	Microstructure
G6	1976	5	507	444	Slight decarburization on face
G6A	1826	8	512	444	Trace of austenite in case - Martensitic Back
G6B	1980	13	590	444	Trace of austenite in case - Martensitic Back.
G7	2094	22	587	444	Trace of austenite in case - Martensitic Back.
G7A	2110	23	600	444	Trace of austenite in case - Martensitic Back.
G7B	2102	22	602	444	Trace of austenite in case - Martensitic Back.
G8	2066	[illegible]	[illegible]	[illegible]	Trace of austenite in case - Martensitic Back.
G8A	2112	25	[illegible]	444	Pearlite banding in face
G8B	2171	28	[illegible]	444	Trace of austenite in case - Martensitic Back.
G9	1993	47	614	444	Trace of austenite in case - Martensitic Back.
G9A	2084	39	621	454	Pearlite banding in face.

TABLE IV (Cont'd.)

Plate No.	Cal. .50 Limited correlated to St'd. Thickness	% Face	Brinell Hardness Face	Brinell Hardness Back	Microstructure
G9B	2020	49	604	444	Trace of austenite in case - Martensitic Back.
G10	1922	47	627	444	Trace of austenite in case - Martensitic Back.
G10A	2018	51	605	444	Trace of austenite in case - Martensitic Back.
G10B	2012	53	59[illegible]	440	Trace of austenite in case - Martensitic Back.

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