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REPORT

ON

HARDNESS AND BALLISTIC PERFORMANCE OF SIX FACE HARDENED ARMOR PLATES

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ABSTRACT

Data of the hardness and ballistic performance of six face hardened airplane engine armor plates are presented.

A study to discover an effect, if any, of back decarburization on the ballistic performance of the samples reveals no large effect that can be ascribed to back decarburization. Some evidence of importance of face decarburization exists. Conclusions with respect to decarburization were difficult because of quality variations in each sample. The principal variable appears to be heat treatment rather than decarburization. Great variations in hardness within short distances across the faces and across the backs of the samples are ascribed to non-uniformity of quench, as evidenced by metallurgical examination.

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DECLASSIFIED

TABLE OF CONTENTS

Page No.

APPENDIX

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TABLE OF CONTENTS (cont'd)

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HARDNESS AND BALLISTIC PERFORMANCE OF

SIX FACE HARDENED ARMOR PLATES

Introduction

1. The problem was authorized by reference (a). Other pertinent references are as follows:

(a) BuOrd lettr. S13-1(4/173)(QB) of 13 December 1934.
(b) Scott and Gray, Trans. A S M 28: 399(1940)
(c) Ninth Partial Report, NRL Report No. O-1778, 4 September 1941.
(d) Tenth Partial Report, NRL Report No. O-1892, 22 June 1942.
(e) BuOrd Specs. O.S. No. 2775, 13 November 1942.
(f) BuOrd lettr. S13-1(3)(B36919) of 2 April 1943.

2. Bullet proof steel is decarburized to various depths in heat treatment. Interest has been expressed in the advantage or disadvantage of this decarburization. At the request of Lt. Harris, Armament Section, Bureau of Aeronautics, six samples of FH-BPS engine armor were forwarded to the Naval Research Laboratory from the Jessop Steel Company for investigation. Unfortunately for the original purpose of this investigation, the plates received exhibited numerous irregularities under test with bullets. The principal variable appears to be heat treatment rather than decarburization. Since a considerable amount of data was compiled in an effort to explain the peculiarities of the results of the test of this group of plates, it was decided to organize the results as shown in this report. This set of armor plates is of low average quality, and it is hoped the various details presented here will be of some assistance to those who are endeavoring to purchase or make improved face hardened light armor.

3. Recently reference (f) has been received, which describes the importance of decarburization of the face of face hardened light armor. The study of face decarburization appears to be of considerable interest. Whether back decarburization measurably affects the quality of FH-BPS is also of interest. The work described in this report began with a study of the effect of decarburization on the backs of face hardened plates. The plates were cut into sections for ballistic tests, and various depths of material were ground from the backs of some of the sections. Determinations of limit velocities at normal impact were made with Cal .30 AP M2 bullets on sections of the 3/8" armor and with Cal .50 AP M1 bullets on the 1/2" armor. Sections which proved of interest in the ballistic tests were investigated by surveys with Vickers hardness indents from faces to backs.

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4. In addition, macro etches were made to determine if non-metallic segregations were present in an amount sufficient to consider in interpretation of ballistic results and to get an idea of the extent of decarburization of the face and back of some of the sections. Also, metallographic specimens were prepared from one section of the 3/8" armor, which had shown great variation in ballistic performance, and photomicrographs were made for study of back composition. These specimens were also heat treated in order to compare carbon content and alloy content of the backs.

5. It was thought that retained austenite as in reference (d) might account for difference in face hardness of some of the plates. To detect retained austenite, the plates were chilled in dry ice, and more hardness surveys were made. The micro-structure of each of the 1/2" armor samples was studied also by examination of microspecimens.

Equipment and Methods

6. The armor samples were sawed into sections shown in the photographs and diagrams in the appendix. Depths of 0.02", 0.04", and 0.06" of material were ground from the backs of some of the sections of each sample in order to see if removal of various depths of the decarburized zone would effect the ballistic resistance of the armor. Sections M7-B1, M9-L2, and M11-D1 were made after the ballistic tests. Impacts numbered 631 and 637 on sample M7 and those numbered 560 and 564 on sample M9 were among the impacts revealing hard and soft regions on the backs of these samples. Hardness and metallurgical tests were made in these regions.

7. Tests of ballistic resistance of the 3/8" face hardened armor plate to Cal .30 AP M2 bullets were made in the 110 lb. pendulum described in reference (c), and tests of ballistic resistance of the 1/2" armor plate to Cal .50 AP M1 bullets were made in a pendulum, weighing about 370 lbs. and constructed in a manner similar to that of the 110 lb. pendulum.

8. The Cal .30 AP M2 bullets used were pulled from loaded ammunition furnished by the St. Louis Ordnance Plant. The steel darts of these bullets have an average weight of 80.4 gr. and an average diameter of 0.2442". The Cal .50 AP M1 bullets used were plate testing bullets of the Frankford Arsenal. They had an average weight of 412 gr. and an average diameter of 0.428".

9. Limit velocity estimates for each sample section of different thickness are tabulated in Tables No. 3 and No. 4 of the appendix. For sections which showed two regions which varied in resistance, two estimates of limit velocity were made, one for each region. In M9-1 and M9-K, however, the limit velocity of the regions which petaled are lower than the lowest limits listed; how much lower could not be estimated from the data. A plot of velocities against

corresponding e/d values is shown in Plate 14.

10. Vickers diamond pyramid hardness tests were made from face to back of sections M7-B1, M7-D, M8-H, M9-L, M9-L1, M10-Q1, M11-B1, and M12-E1 in positions shown in the diagrams of the appendix. The surfaces for hardness indents were given a fine finish by wet grinding.

11. For metallurgical examinations sections M7-B1, M8-H, M9-L2, M11-D1, M11-B1, and M12-E1 were submitted to Mr. I. R. Kramer of the Special Alloys Section of the Physical Metallurgy Division of the Naval Research Laboratory. Macro etches were made of M7-B1, M8-H, M9-L2, and M11-D2; the surfaces etched are indicated by marking them S in the diagrams made of these sections. A 10 percent solution of ammonium persulfate in water was used to etch all four sections. On M7-B1 and M8-H nital was also used. Metallographic specimens were prepared of pieces M9-L2-A and M9-L2-B, which were cut from section M9-L2 in the regions of impacts number 560 and 564. The scale was removed from the backs of these pieces, and the surfaces to be examined were polished by grinding them on successive finer grades of alundum paper to grade No. 0000 and were finally polished electrolytically in a solution of acetic anhydride and perchloric acid. Photomicrographs were made at a distance of 0.02" from the backs of each specimen. These photomicrographs are shown in the appendix. To test for possible carbon segregation in the back of each piece, M9-L2-A and M9-L2-B were oil quenched from 1600° F, and comparison of hardnesses were made at 0.015" from the back edge of each piece. The sections were then held one hour at 570° F for comparison of their resistances to tempering. Microscopic examinations were made of the micro-structure in the faces of M11 and M12. The microspecimens were prepared from pieces cut from sections M11-B1, and M12-E1. Nital was used to etch the surfaces of these specimens.

Discussion of Data

12. Data are given in forms of photographs, diagrams, tables, and graphs in the appendix.

13. An examination of the results of the ballistic tests tabulated in Table 1 and Table 2 shows that each of the Jessop samples varied in quality within small regions. It is unlikely that any of these plates would pass the specifications of reference (e). In Tables No. 3 and No. 4 are listed striking velocities required by the Bureau of Ordnance for testing the plate thicknesses listed in these tables. The values of the striking velocities were obtained by straight line interpolation between tabulated values appearing in Table 1 of reference (e). According to the O. S. No. 2775, a face hardened armor plate would fail if a round fired at the tabulated velocity plus 15 ft/sec or less results in complete penetration. Consider such quality contrasts as revealed by impacts No. 534 and 630 on M7-B.

The bullet of impact No. 534, moving with a velocity of only 2112 ft/sec resulted in complete penetration of the plate, whereas the bullet of impact 630, moving with a velocity of 2162 ft/sec produced only a bulge measuring .009" high. On section M8-G, impacts numbered 541 and 543 were of bullets with about the same velocity, 2111 and 2110 ft/sec; one penetrated the plate completely; the other produced only a bulge measuring 0.016" high. Section M9-L showed a striking difference in quality. In impacts 560 and 559 on this plate, plugs were formed; whereas, about 1-1/4" away in a line parallel to them, in impacts 562 and 564, petals were formed and retained. Impacts 601 and 602 on M10-S were among those revealing differences in ballistic resistance of sample M10; the bullet of impact 601 with a velocity of 2053 ft/sec knocked a plug out of M10-S; whereas the bullet of impact 602 with a velocity of 2082 ft/sec produced a bulge 0.028" high.

14. A picture of the performance of good FH-BPS against Cal .30 darts was given by the data of the ballistic performance of the FH-BPS described in reference (d). In the few cases in which a bullet that threw a plug and had a velocity less than that of a bullet which produced only a bulge in the same plate, the difference in velocities was usually not more than 20 ft/sec.

15. Even greater differences in ballistic resistance were shown by the 1/2" samples, M11 and M12. In round 140 a Cal .50 bullet with a velocity of 1759 ft/sec completely penetrated section M11-B, whereas in round 147 a bullet with a velocity of 1873 ft/sec produced a bulge. In round 198 on M12-F a Cal .50 bullet with a velocity of 2006 ft/sec knocked a plug out of M12-F, but in round 191 a bullet with a velocity of 2088 ft/sec made a small bulge.

16. A comparison of the performance of the armor samples is afforded by the plot of the velocities against e/d values on Plate 14 of the appendix. Of the 1/2" samples, M12 is clearly superior to M11. Of the 3/8" samples M8 and M9 are better than M7 and M10. An effect on ballistic performance by removal of the decarburized layer would be noticed on this plot, if such an effect were greater than the irregularities due to variations in face and back hardnesses.

17. A comparison of the hardness surveys of samples M12 and M11 shows that in the regions tested, M12 has a harder face than M11 by about 130 DPH. At depths increasing from 0.07" to the back of the plate, the hardness values are about the same in each plate. Thus, a higher face hardness of sample M12 may be responsible for its higher ballistic resistance. Comparing hardness surveys on M7 and M8, one might explain the lower ballistic performance of M7 by its lower face hardness at depths of 0.01" or less. The hardness survey shows that at a depth of 0.01" M7 was softer than M8, though it had a harder back, and the peak face hardnesses were about the same.

18. Along with variations in face hardness, variations in back hardness may be responsible for differences in ballistic performance. Marked variations in face hardness and in back hardness were observed in sample M9. In the regions of impacts 560 and 564 there was a difference of 125 DPH in face hardness, and even the peak values at 0.02" from the faces differed by 125 DPH. In the region in which petals appeared on the back and the dart passed through unbroken, the highest value of the carburized face layer was about 550 DPH; at a corresponding depth in the region in which a plug was thrown the hardness value was about 675 DPH. Beyond a depth of 0.16" from the face, hardness values differed by only about 30 DPH. On section M9-L1 hardness surveys were made on a surface formed by a cut made parallel to the cut through the holes of impacts 560 and 564. The survey called Row 1 on Plate 19 of the appendix was about 3/4" from Impact 560; Row 3 was about 3/4" from Impact 564. Row 3 showed a slightly higher face hardness but a much lower back hardness than Row 1. The difference in back hardness was about 100 DPH.

19. It is of interest to note that the faces of all the samples had hardness values lower than 600 Brinell. By use of the conversion chart and table of reference (b), the DPH values at a depth of 0.01" or 0.02" were converted to BH values shown in Table 5. No hardness values higher than 600 Brinell (standard ball) were revealed, and it is reasonable to expect that the face hardness values were even lower. In reference (f) it was pointed out that in the tests at NPG the pluramelt experimental armor plates with face hardnesses under 600 Brinell failed to pass specifications.

20. The macro etches made did not show non-metallic segregation in an amount sufficient to consider in interpretation of the ballistic performance of the Jessop samples. Macro etches of M7-B1 and M8-H with nital showed a slight amount of decarburization of the faces; the lightly etched layer measured 0.003" on M7-H, and 0.005" on M8-B1. The lightly etched region of the back of M8-H measured as much as that of the face and was probably deeper since the shading into the lightly etched region of the back was more gradual than that of the face. The back hardness of M7 and of M8 began to drop rapidly as far as 0.06" from the back surface. The back hardnesses of the other samples began to drop rapidly about 0.02" from the back surface. The decarburized zone would lie within these regions.

21. Nonuniformity of quench seems to be the principle reason for variation in ballistic performance. From his study of the microphotographs taken at a distance of 0.02" from the backs in regions of impacts 560 and 564 on M9-L, Mr. Kramer described his findings as follows:

"The structure of L2-B showed tempered martensite with ferrite surrounding the grain boundary, while L2-A showed only tempered

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martensite. The presence of ferrite around the austentic grain boundaries shows that the cooling of this section was too slow to prevent partial transformation. This may be caused either by improper quenching or gross segregation. Specimens of L2-A and L2-B were heated to 1600° F and quenched in oil. The hardnesses at the backs at 0.015" were equal, L2-A being 45.6 Rc, and L2-B being 45.5 Rc. The specimens after tempering at 570° F for one hour again gave equal hardness values at the backs. Since the hardness on quenching is dependent only upon the carbon content, it is seen that the carbon content of the two specimens were equal. Further, the resistance to tempering will depend upon both the carbon and alloy content, and since the hardnesses after tempering are equal, the alloy contents must have been the same. Therefore, it is believed from these tests that no segregation has taken place, and the difference in hardness found along the back (described in paragraph 21) must have been due to non-uniformity of quench."

22. Microscopic examination near the face surface of the micro-specimens prepared from sections of M12-E and M11-B1 showed decarburization at the outside of the carburized surface with only a very slight amount of grain boundary ferrite. Coming into the plate from this surface, one finds martensite together with increasing amounts of austenite. The austenite content and possibly the carbon content, as well, are maximum for both specimens at 0.02". For E1-1 the austenite disappears at about 0.097". For B1-2 the austenite disappears at only 0.073". Otherwise, the microstructures of the two samples are very similar.

23. The hardness surveys made before and after chilling sections M9-L1, M12-E1, and M11-B1 in dry ice showed transformed austenite in these plates. In M9-L1 at a depth of 0.04" from its face the hardness increased from 700 to 800 DPH; in M11-B1 at a depth of 0.03" from its face the hardness increased from not more than 580 to 650 DPH, and in M12-E1 at a depth of 0.02" from its face the hardness increased from 620 to 650 DPH.

<u>Conclusion</u>

24. This report shows the results of ballistic tests of six FH-BPS plates and in association with these tests, measurements of general hardness of face, general hardness of back, and, to some extent, of decarburization of face and back. All of these hardness properties showed large variations in the sample plates described in this report.

25. Conclusions with respect to decarburization effects are difficult because of variations in results due to quality scatter and difficulties in determining face and back hardnesses. Vicker's hardness numbers were not reliable other than on a relative basis at .01" from the plate surfaces. However, there is evidence that no large

effects can be ascribed to back decarburization. Some evidence of importance of face decarburization exists but will add little to the more detailed work along this line at the Naval Proving Ground.

26 The major portion of the faults of the plates studied were such as to be remediable by reheat treatment and are probably due to non-uniformity of quench. Some of the hardness deficiencies of the face sections of FH-BPS are due to retained austenite.

Recommendations

27. The selection at the Jessop Plant of the six plates studied in this report may have been on such a basis as to make them probably below average engine armor plate quality. In view of this and the limited number of plates examined, the conclusions of this report should not be judged as description of average quality. Nevertheless, in view of the surprisingly large variations across even short distances within the plates examined, the conditions of heat treatment which produced such non-uniformity would be well worth correction. Some emphasis upon selection of small as well as large finished plates for ballistic tests might serve to direct attention to more careful handling of small pieces of face hardened plates.

Summary

28. Data of the hardness and ballistic performance of six face hardened airplane engine armor plates have been presented.

29. The studies shown in this report revealed no large ballistic effects that can be ascribed to back decarburization. Some evidence of importance of face decarburization was noted. Decarburization effects upon the results tended to be masked by quality variations in the individual samples. On the whole, the principal variable appeared to be heat treatment rather than decarburization. The large variations in hardness found within short distances across the faces and backs of the samples studied in this report were ascribed to non-uniformity of quench, as evidenced by metallurgical examination.

TABLE 1

3/8" Face Hardened BPS: Cal .30 AP M2 Bullets

Sample	Thickness (in.)	Impact Number	Bullet Velocity (ft/sec)	Remarks
M7-A	0.386	528	2312	Full hole; secondary petals; dart in 4th pad.*
	0.386	529	2275	0.016" bulge; dart broke up.
	0.362	530	2302	Undersize plug in 1st pad.
	0.360	531	2181	Full hole; irregular plug in 1st pad.
	0.361	532	2215	Full hole; plug thru 1st pad; back of dart not thru plate.
M7-B	0.349	533	2220	Full size hole, low velocity plug.
	0.342	534	2112	Full hole, irregular plug thru 1st pad.
	0.335	535	2095	0.013" bulge.
	0.330	631	2278	Small hole, plug into 1st pad, most of dart not thru plate.
	0.320	536	2075	0.005" bulge.
	0.314	630	2162	0.009" bulge.
	0.309	537	2049	0.007" bulge.
	0.310	538	2063	0.007" bulge.
M7-C	0.322	539	2074	0.013" bulge.
	0.328	540	2074	0.010" bulge.
M8-E	0.373	553	2245	Plug Started.
	0.373	554	2287	Plug into 1st pad; back of dart hung in.
	0.373	555	2278	0.033" bulge.
	0.352	550	2270	Full hole; plug into 1st pad.
	0.347	551	2148	0.019" bulge.
	0.347	552	2250	Full hole; plug into 1st pad.
M8-F	0.329	547	2145	Plug crack nearly complete.
	0.327	549	2228	Plug crack nearly complete.
	0.311	544	2018	0.007" bulge.
	0.311	548	2189	0.025" bulge.
	0.306	546	2085	0.017" bulge.
	0.305	545	2122	Plug nearly knocked out.

* Paper pads, measuring 3" x 5" x 1/2", were used as backstop material.

[redacted]

TABLE 1 (cont'd)

3/8" Face Hardened BPS, Cal .30 AP M2 Bullets

Sample	Thickness (in.)	Impact Number	Bullet Velocity (ft/sec)	Remarks
M8-G	0.373	556	2278	Full hole, plug in 1st pad.
	0.373	557	2269	Full hole, plug in 2nd pad.
	0.373	558	2262	0.025" bulge
	0.310	541	2111	Secondary petaling; dart unbroken in 4th pad.
	0.307	542	2059	0.011" bulge
	0.305	543	2110	0.016" bulge
M9-L	0.375	559	2286	Plug crack complete; plug nearly out.
	0.375	560	2291	Full hole; dart thru plate and 6 pads into wedge.
	0.375	561	2300	Plug started.
	0.375	562	2263	Full petals; unbroken dart thru to 4th pad.
	0.375	563	2232	Plug almost knocked out.
	0.375	564	2285	Full petals; unbroken dart thru.
M9-K	0.353	565	2209	0.077" bulge.
	0.353	568	2198	Full petals; dart on floor.
	0.350	566	2223	Full petals, dart unbroken on floor.
	0.345	569	2232	Full petals, dart unbroken.
	0.339	567	2220	Full petals, dart unbroken.
M9-M	0.333	570	2269	Full hole, dart thru to 5th rubber.
	0.333	572	2173	Full hole, dart and plug in 2nd pad.
	0.328	573	2152	0.013" bulge, dart broke up.
	0.328	574	2114	Full hole; dart thru to 4th pad.
	0.317	571	2192	Small hole; plug in 1st pad.
	0.308	575	2102	0.014" bulge, dart broke up.
M9-N	0.323	577	2061	0.011" bulge, dart broke up.
	0.322	576	2172	Full hole; dart thru 4 pads.
	0.320	578	2091	Small plug crack started, dart broke up.
	0.320	579	2088	0.005" bulge; dart broke up.
	0.318	580	2111	0.051" bulge; dart broke up.

[redacted]

TABLE 1 (cont'd)

3/8" Face Hardened BPS, Cal .30 AP M2 Bullets

Sample	Thickness (in.)	Impact Number	Bullet Velocity (ft/sec)	Remarks
M9-N	0.311	582	2140	Small plug started; dart broke up.
	0.305	581	2114	0.024" bulge; dart broke up.
M9-J	0.313	583	2115	Full hole, dart thru to 4th pad; secondary petaling; [illegible]
	0.315	584	2115	Plug started.
	0.315	585	2083	Small crack started.
M10-Q	0.377	586	2267	Plug started, dart broke up.
	0.377	587	2285	Full hole, plug and dart in 1st pad.
	0.377	588	2212	0.024" bulge; dart broke up.
	0.377	589	2267	Full hole; plug and dart in 2nd pad.
	0.377	590	2245	Full hole; plug and dart in 2nd pad.
M10-P	0.355	591	2290	Full hole; dart and plug thru several pads.
	0.355	592	2225	Full hole; dart and plug in 2nd pad.
	0.355	593	2187	0.067" bulge; dart broke.
	0.354	595	2238	Full hole; dart broke; plug in 3rd pad.
	0.354	596	2210	Full hole; dart broke; plug in 1st pad.
M10-R	0.337	597	2162	Full hole, plug in 2nd pad; dart in 4th pad.
	0.337	598	2099	Full hole; plug and dart in 3rd pad.
	0.335	599	2082	0.048" bulge; dart broke up.
	0.334	600	2099	Full petals; dart thru unbroken.
	0.332	632	2162	Small hole; plug into 1st pad; back of dart not thru plate.
	0.333	633	2242	Full hole; plug on floor; dart in 4th pad.

[redacted]

TABLE 1 (cont'd)

3/8" Face Hardened BPS, Cal .30 AP M2 Bullets

Sample	Thickness (in.)	Impact Number	Bullet Velocity (ft/sec)	Remarks
M10-S	0.335	601	2053	Undersize hole; dart knocked plug into 1st pad.
	0.323	603	2030	0.037" bulge; dart broke up.
	0.322	604	2098	Undersize plug, low velocity; most of dart stuck in plate.
	0.321	602	2082	0.028" bulge; dart broke up.

[redacted]

TABLE 2

1/2" Face Hardened BPS; Cal .50 AP M1 Bullets

Sample	Thickness (in.)	Round Number	Bullet Velocity (ft/sec)	Remarks
M11-B	0.501	140	1759	Full hole.
	0.501	141	1670	Bulge.
	0.501	142	1699	Bulge.
	0.501	143	1600	Bulge.
	0.501	144	1720	Bulge.
	0.501	145	1748	Bulge.
	0.501	146	1768	Bulge.
	0.501	147	1873	Bulge.
	0.501	148	1917	Full hole.
	0.501	149	1840	Bulge.
	0.501	150	1900	Full hole.
M11-A	0.472	153	1839	Full hole.
	0.462	152	1850	Undersize hole.
	0.459	156	1760	Bulge.
	0.452	154	1770	1/4" plug.
	0.443	151	1864	Full hole; ear of sample broke off.
	0.443	155	1695	Bulge.
	0.443	157	1740	3/16" plug.
M11-C	0.480	168	1839	Large bulge.
	0.478	167	1860	Bad appearance; dart thru plate and thru rubber to metal back stop.
	0.478	170	1845	Large bulge.
	0.475	165	1928	Full hole.
	0.470	164	1830	Bulge.
	0.468	171	1822	Large bulge.
	0.455	166	1850	1/2" plug thrown to 2nd rubber
	0.443	169	1798	Large bulge.
M11-D	0.472	158	1752	Small bulge.
	0.472	161	1839	Large bulge.
	0.467	159	1772	Small bulge.
	0.466	162	1935	5/16" plug; plug stuck in 1/32" dural.
	0.462	160	1792	Large bulge.
	0.462	163	1892	Large bulge.
M12-D	0.527	172	1900	Small bulge.
	0.527	173	1948	Small bulge.

[redacted]

TABLE 2 (cont'd)

1/2" Face Hardened BPS; Cal .50 AP M1 Bullets

Sample	Thickness (in.)	Round Number	Bullet Velocity (ft/sec)	Remarks
M12-D	0.527	174	2055	Plug crack started.
	0.527	175	2064	Small bulge.
	0.527	176	2186	Full hole; plug thru dural.
	0.527	177	2123	Plug crack started.
	0.527	178	2236	Dart thru to boiler plate.
	0.527	179	2159	3/8" plug; plate cracked to edge.
	0.527	180	2093	Bulge; plate cracked to edge.
M12-E	0.507	188	2062	Small bulge.
	0.504	189	2169	3/8" plug thrown to boiler plate.
	0.500	187	1986	Small bulge.
	0.495	185	1996	Small bulge.
	0.490	181	2077	3/8" plug thrown thru rubber to boiler plate.
	0.490	182	2007	Large bulge.
	0.487	183	2116	3/8" plug thrown to boiler plate; corner cracked off.
	0.487	186	2071	3/8" plug thrown to boiler plate.
	0.485	184	2017	1/4" by 1/2" plug stuck in dural; plate cracked to edge.
M12-F	0.495	191	2088	Small bulge.
	0.473	190	2014	3/8" plug thrown to 3rd rubber
	0.473	193	2010	Plug crack nearly complete.
	0.470	192	2006	1/2" plug thrown to boiler plate.
	0.465	194	1999	Small bulge.
	0.463	195	2087	3/8" plug thrown to last rubber.
M12-C	0.490	199	2037	Small bulge.
	0.490	200	2132	1/2" plug thrown to 3rd rubber
	0.463	196	1982	Small bulge.
	0.460	198	2006	1/2" plug thrown to 6th rubber
	0.458	197	2015	Plug crack started.

[redacted]

TABLE 3

3/8" FH-BPS; Cal .30 AP M2 Bullets

Sample	Thickness (e) (in.)	e/d d = 0.2442"	Limit Velocity (ft/sec)	Specification Velocity O.S. 2775
M7-A	0.386	1.582	2290 ± 25	2302
M7-A	0.361	1.479	<2181	2241
M7-B	0.335	1.372	2100 ± 25	2178
M7-C	0.322	1.320	>2074	2149
M7-B	0.320	1.311	>2075	2142
M8-E	0.373	1.528	2280 ± 30	2270
M8-G	0.373	1.528	2270 ± 30	2270
M8-E	0.352	1.442	2180 ± 25	2219
M8-F	0.329	1.348	2160 ± 30	2163
M8-F	0.327	1.340	2260 ± 30	2158
M8-F	0.311	1.274	>2189	2120
M8-G	0.310	1.271	2080 ± 25	2117
M8-G	0.305	1.250	>2110	2105
M8-F	0.305	1.250	2130 ± 25	2105
M9-L	0.375	1.537	2290 ± 30	2275
			2250 ± 30	
M9-K	0.353	1.446	2200 ± 25	2222
M9-M	0.330	1.352	2160 ± 25	2173
			2120 ± 25	
M9-N	0.318	1.303	2150 ± 30	2137
			2120 ± 25	
M9-J	0.315	1.291	2115 ± 25	2129
M10-Q	0.377	1.545	2230 ± 25	2280
			2270 ± 25	
M10-P	0.355	1.455	2200 ± 25	2229
M10-R	0.335	1.372	2090 ± 25	2178
M10-S	0.322	1.320	2095 ± 25	2147
M10-O	0.316	1.296	2090 ± 30	2132

[redacted]

TABLE 4

1/2" FH-BPS; Cal .50 AP M1 Bullets

Sample	Thickness (e) (in.)	e/d d = 0.428"	Limit Velocity (ft/sec)	Specification Velocity O.S. 2775
M11-B	0.501	1.171	1885 ± 25	2061
			<1760	
M11-A	0.462	1.079	1800 ± 30	2001
M11-A	0.443	1.035	1720 ± 25	1972
M11-C	0.478	1.117	1810 ± 30	2026
			1880 ± 30	
M11-C	0.470	1.098	>1830	2014
M11-D	0.472	1.103	>1840	2016
M11-D	0.462	1.079	1920 ± 25	2001
M12-D	0.527	1.231	2135 ± 25	2096
M12-E	0.507	1.184	>2062	2069
M12-E	0.495	1.156	>1996	2052
M12-E	0.490	1.145	2025 ± 30	2044
M12-F	0.473	1.105	2015 ± 30	2018
M12-F	0.465	1.086	>2000	2006
M12-C	0.490	1.145	<2130	2044
M12-C	0.460	1.075	2010 ± 25	1998

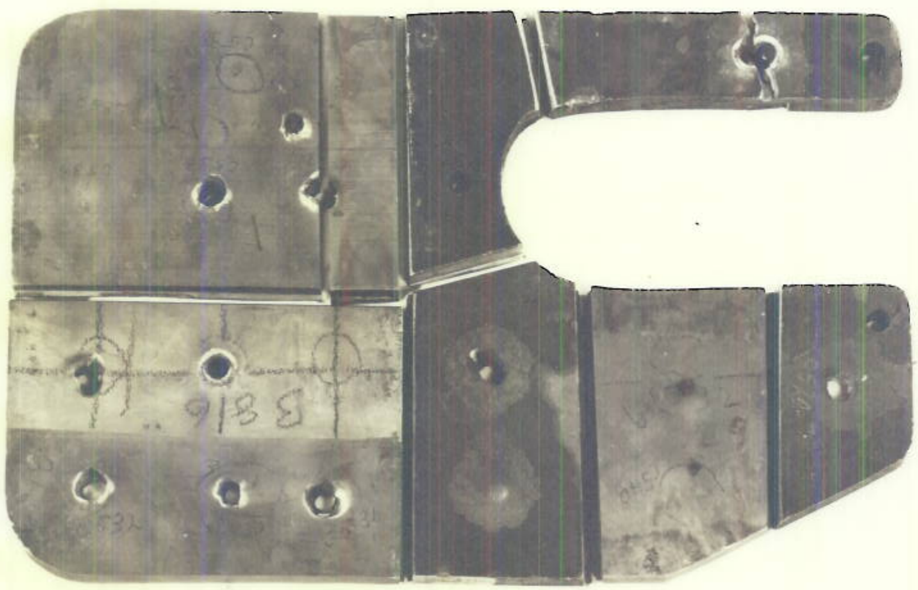
[redacted]

TABLE 5

Conversion of DPH Values to Brinell Hardness Values

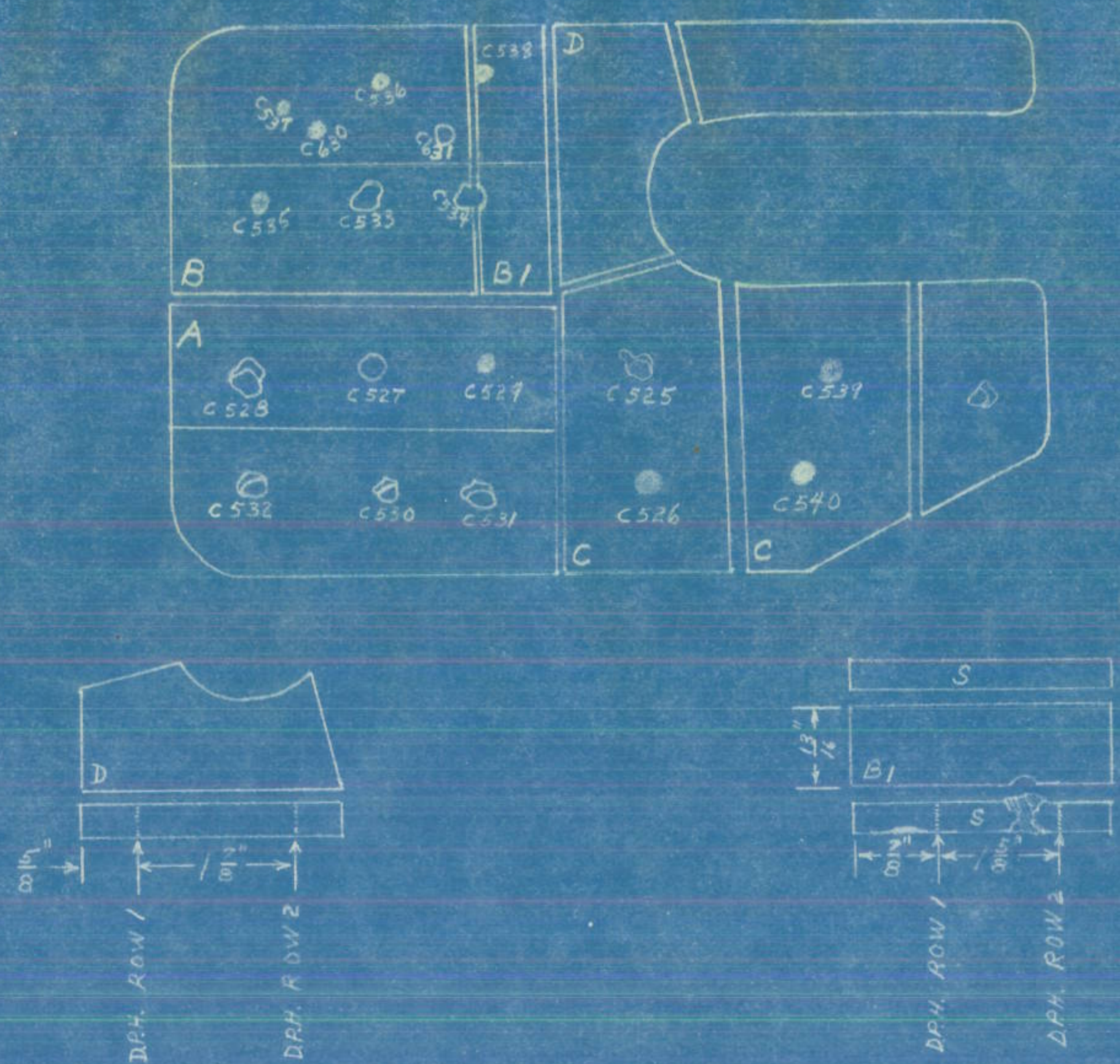
Plate	D.P.H. at 0.01"	B.H.	D.P.H. at 0.02"	B.H.	D.P.H. at 0.03"	B.H.
M7-B1	450 570	429 530	550 625	514 570		
M7-D	490 600	460 553	600 670	553 598		
M8-H	630 640	576 580			675 675	600 600
M9-L	497 622	466 568				
M9-L1	625	570	720 660	=622 592	690 690	607 607
M10-Q	600 630	553 576			620 670	567 598
M11-B1	460 500	439 473			510 540	481 506
M12-E1			620 640	567 580	610 630	560 576

[redacted]



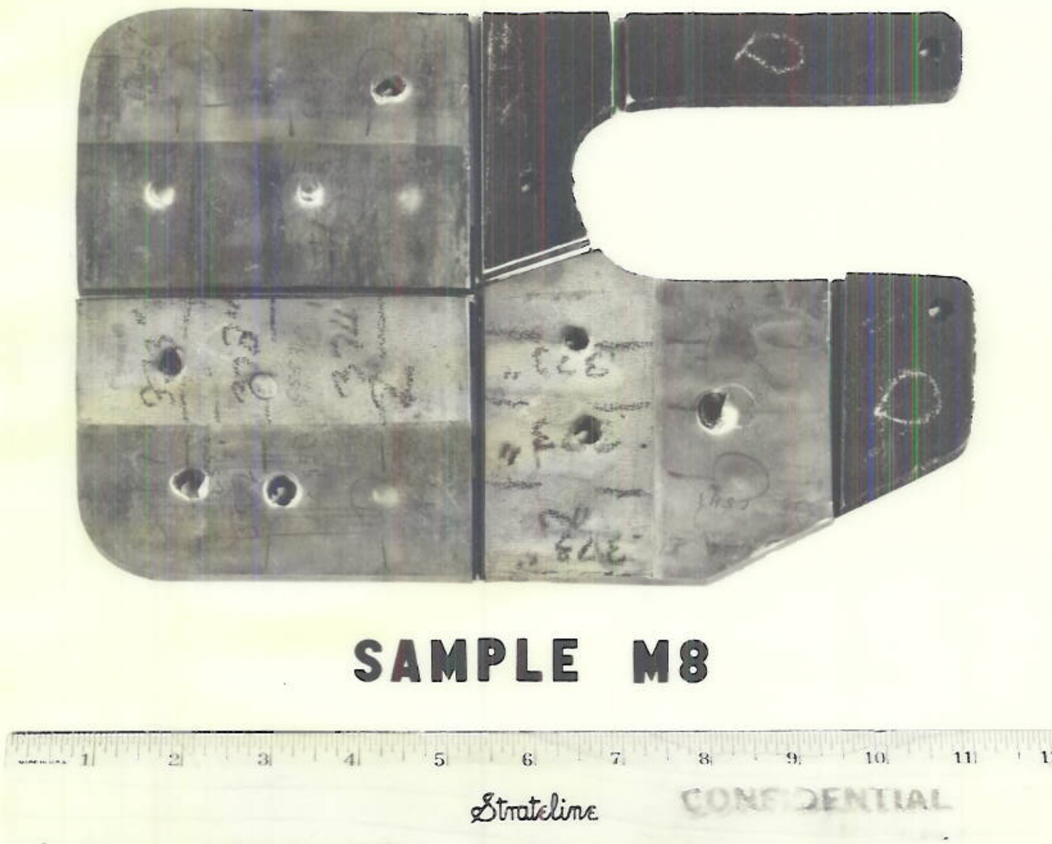
SAMPLE M7

DECLASSIFIED



SAMPLE M7

PLATE 2


SAMPLE M8
Strateline
CONFIDENTIAL

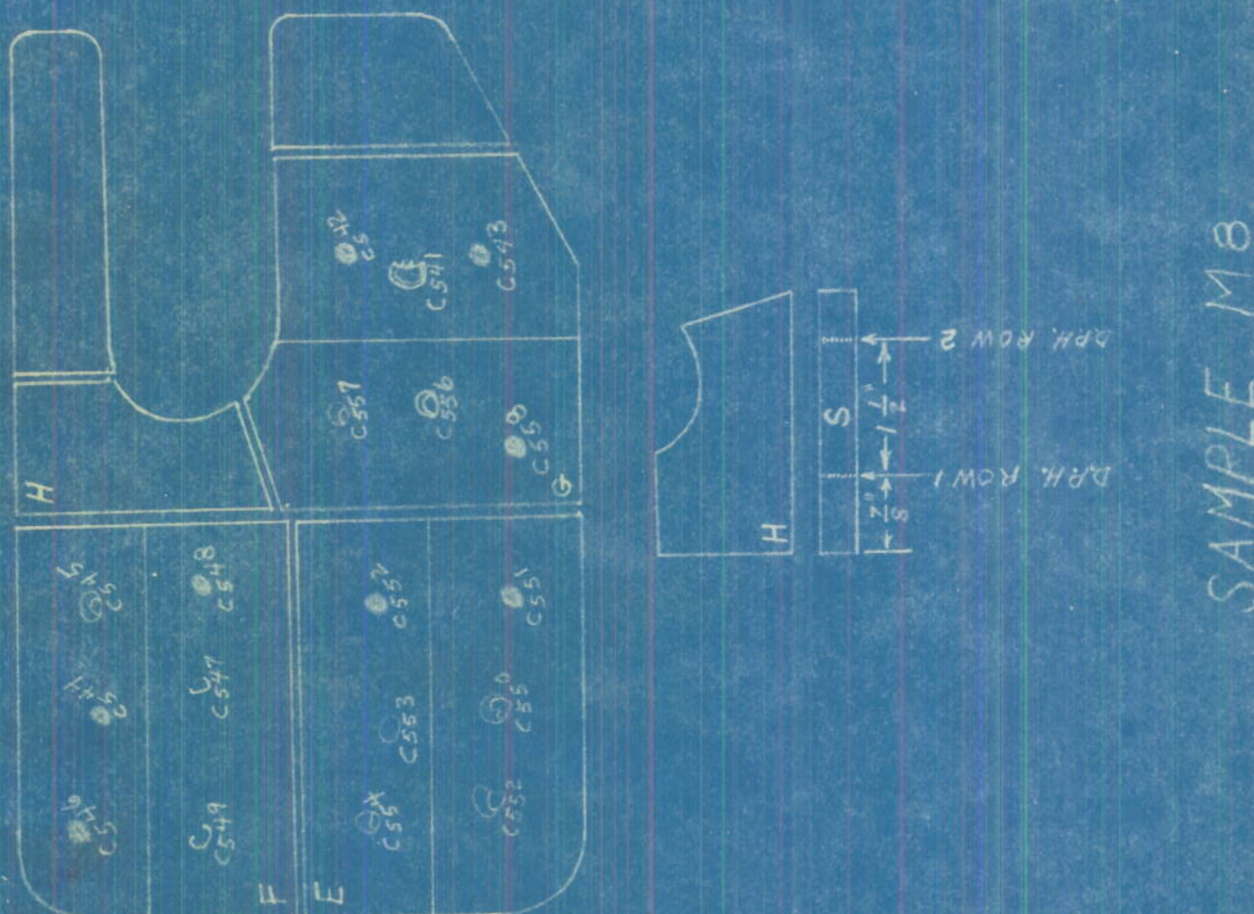

SAMPLE M8
H
S
D.P.H. ROW 1
D.P.H. ROW 2
E
F
G
C541
C543
C547
C548
C549
C551
C552
C553
C557

PLATE 4

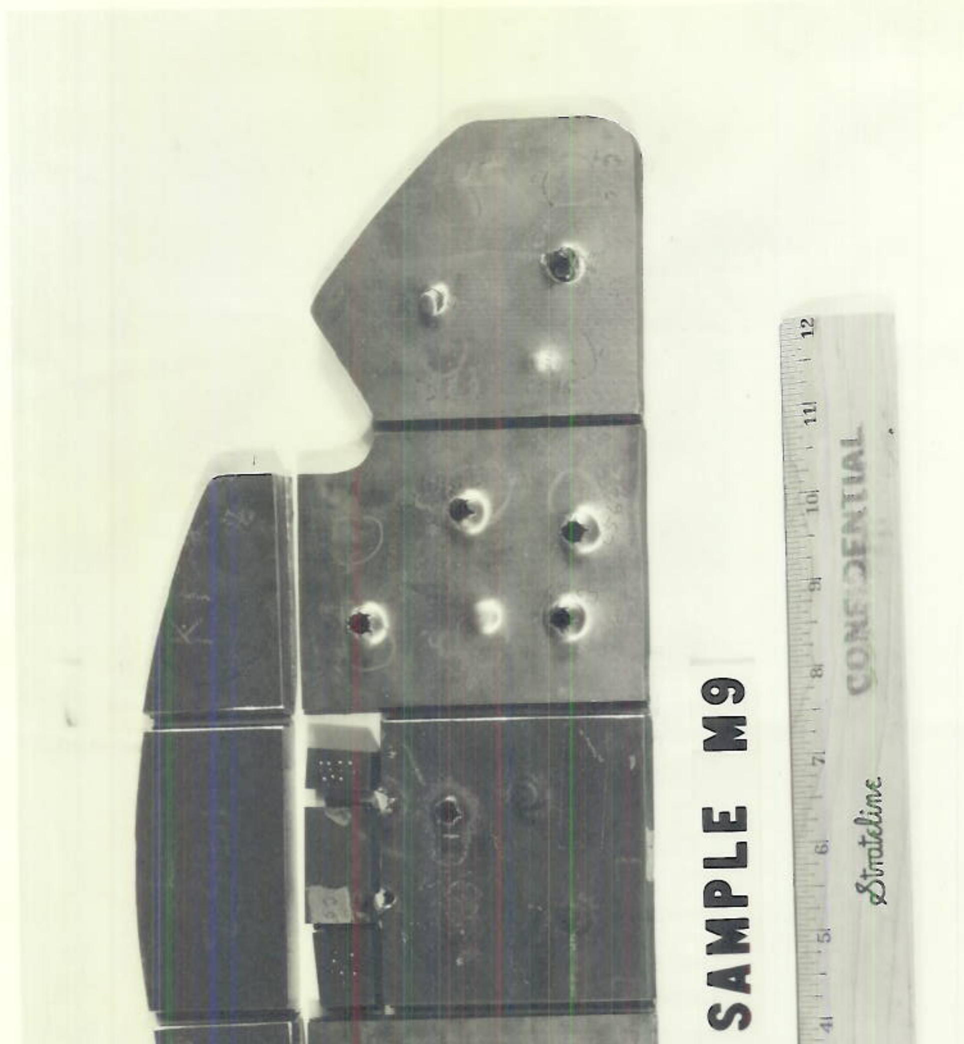
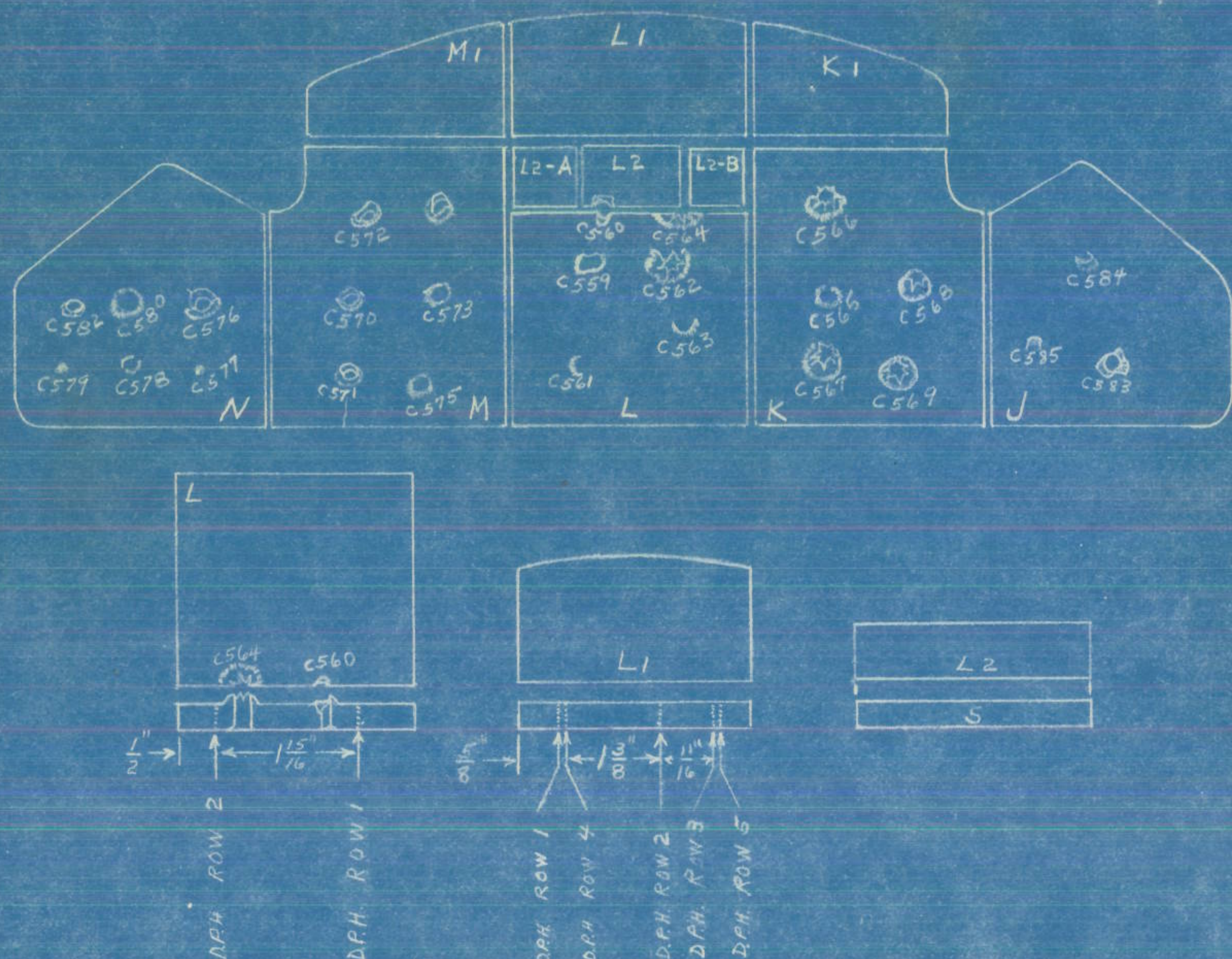


PLATE 5



SAMPLE M9

PLATE 6

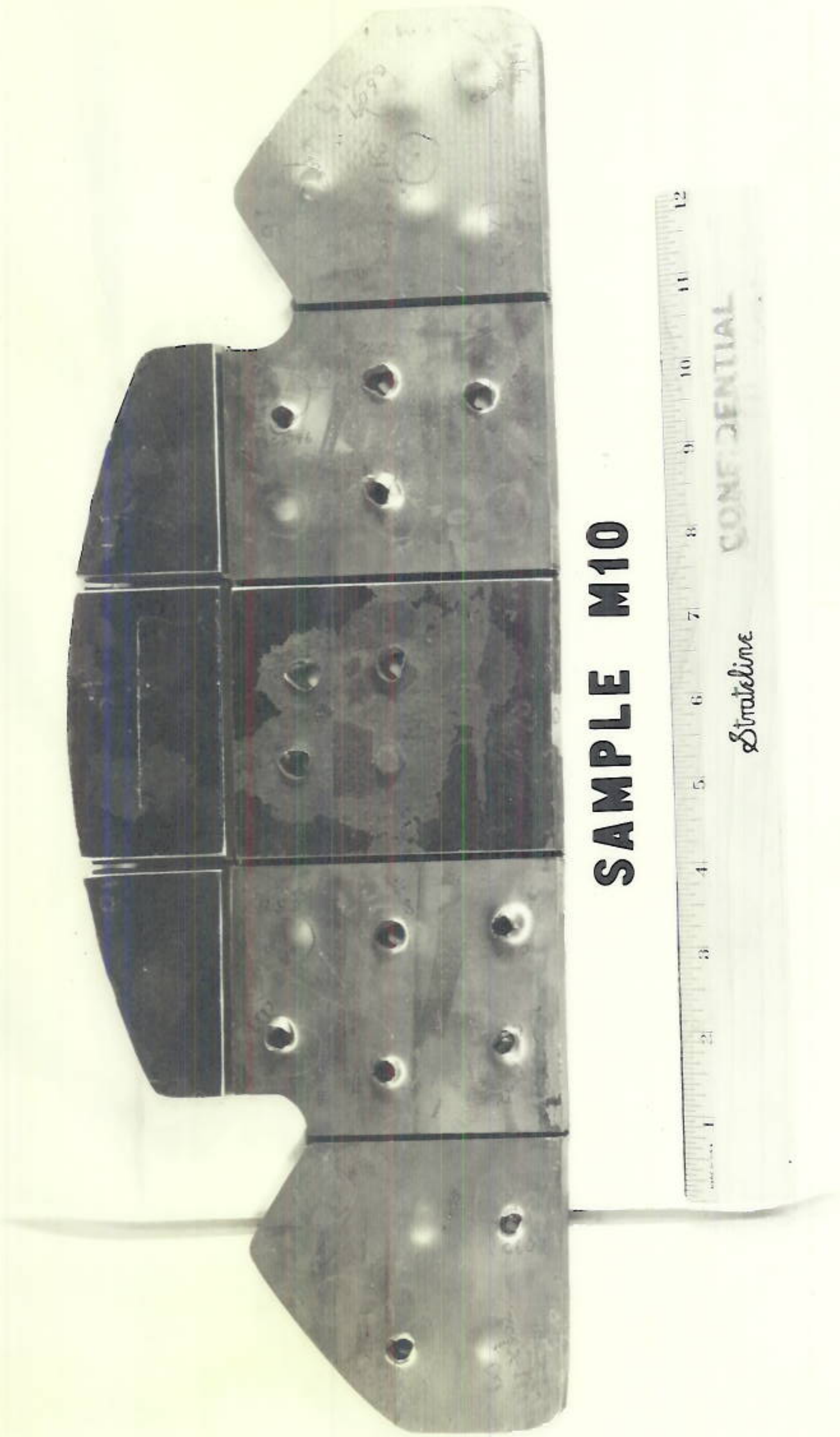
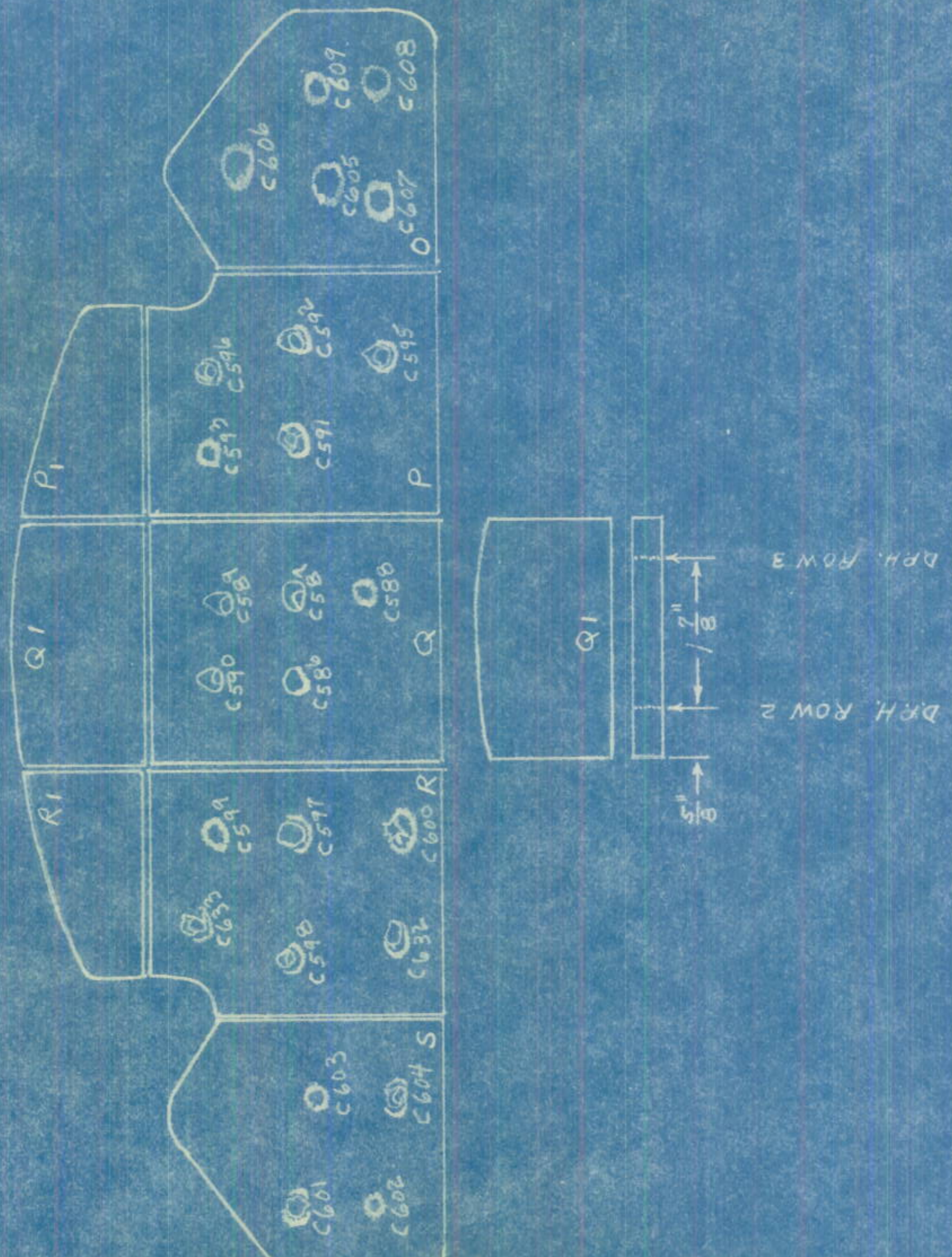


PLATE 7



SAMPLE M10

PLATE 8

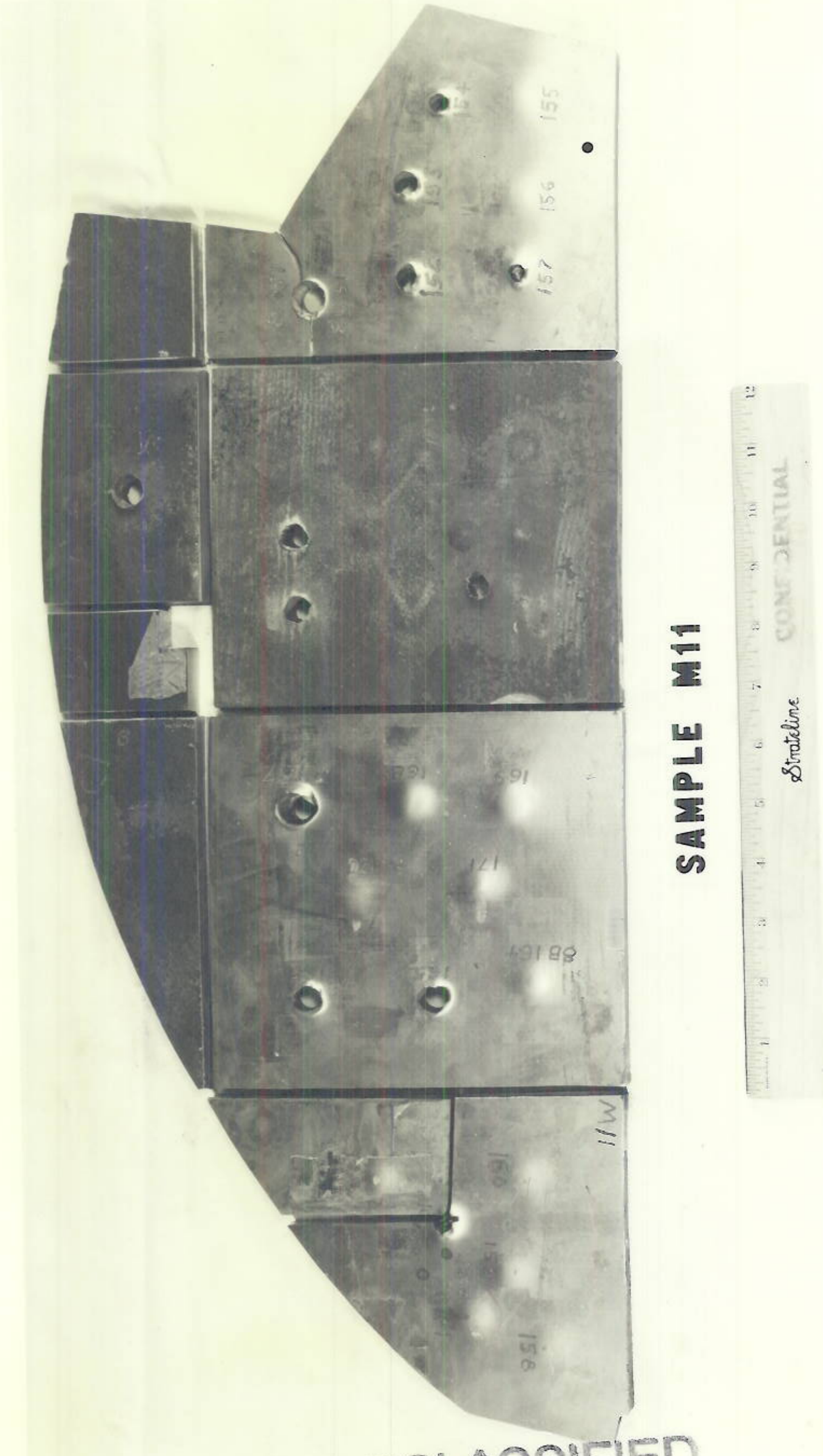
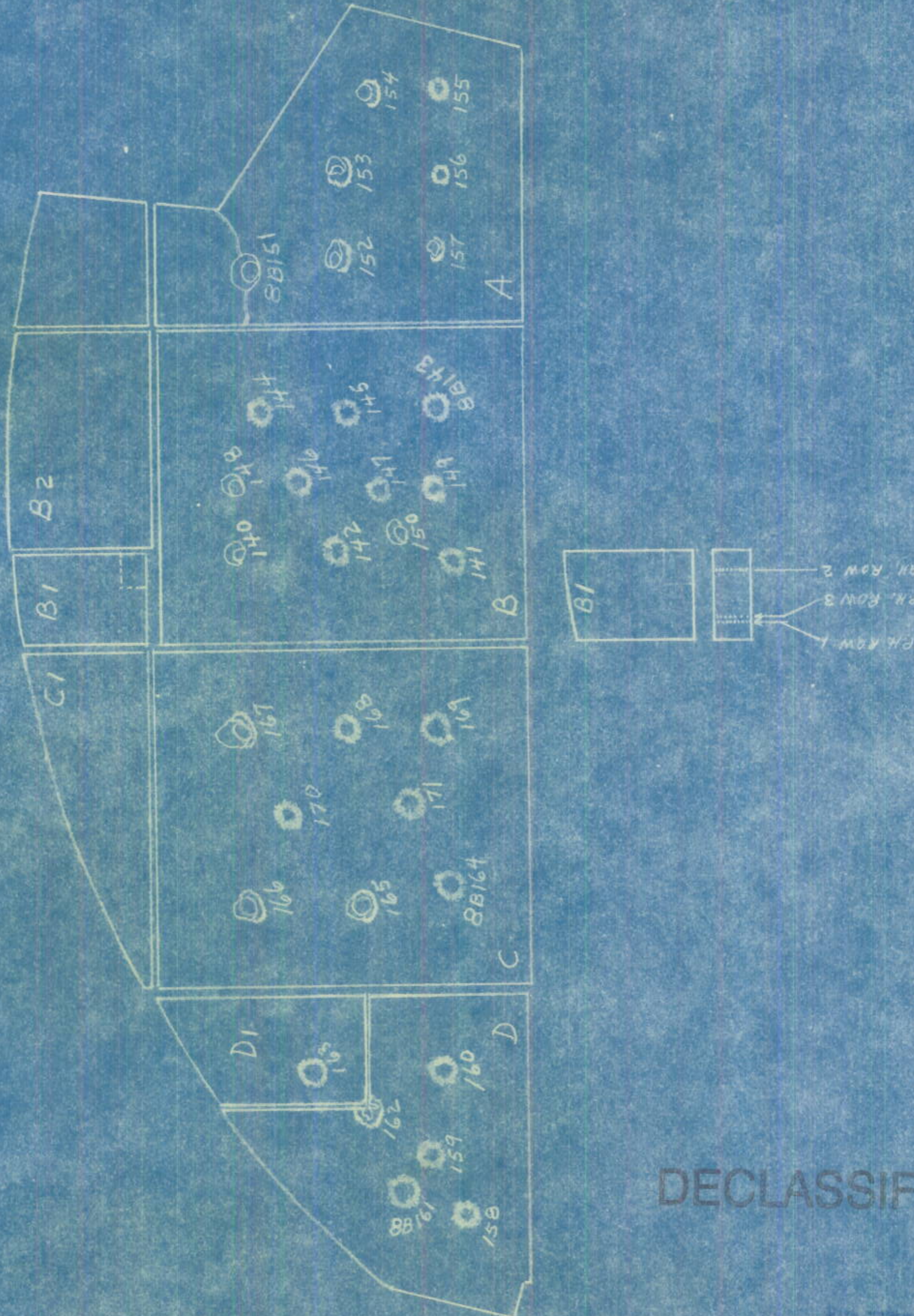


PLATE 9



SAMPLE M11

PLATE 10

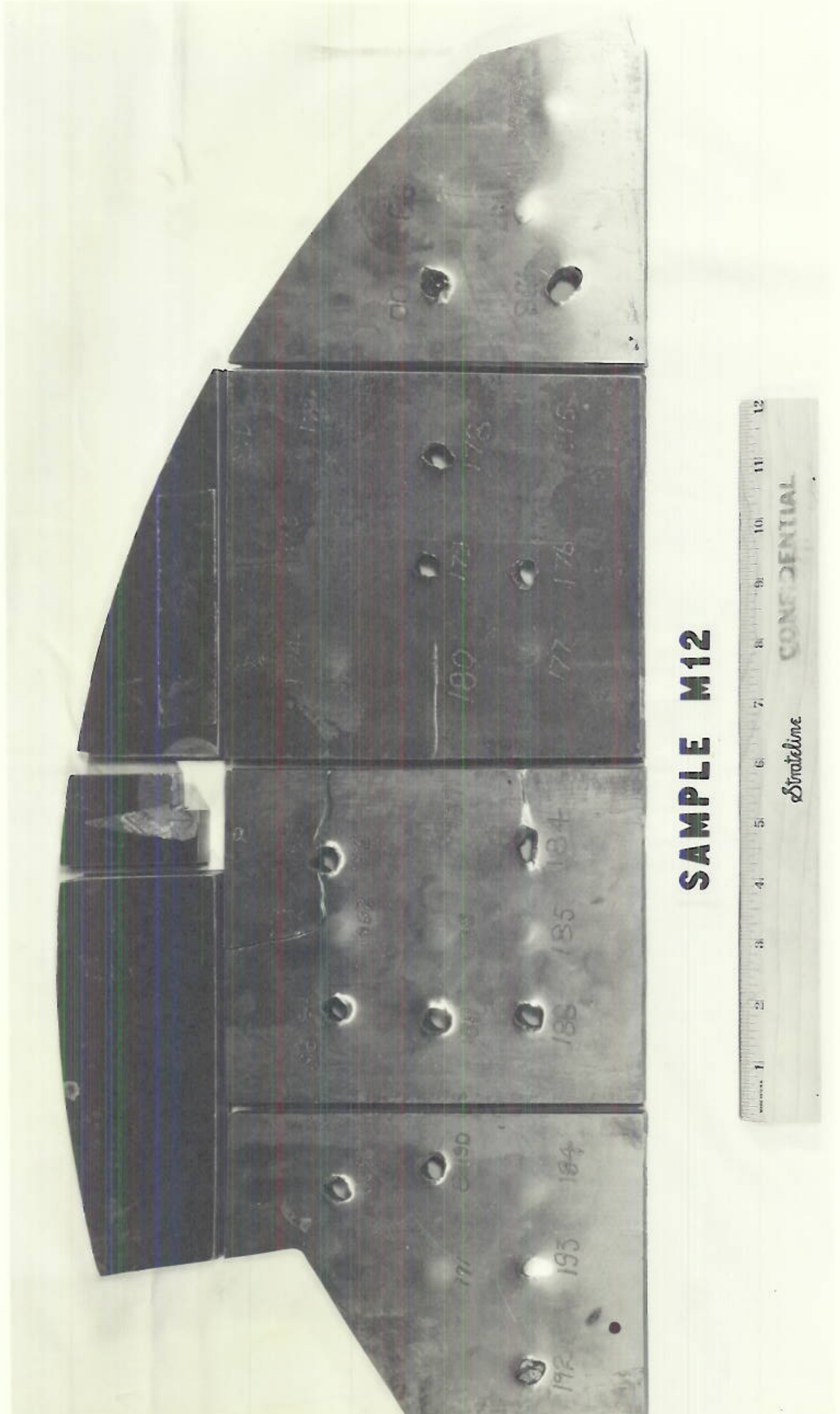


PLATE 11


SAMPLE M12
DPH ROW 1
DPH ROW 2
DPH ROW 3
C
D
D1
E
E1
E2
F
88196
199
200
197
198
172
178
175
179
176
174
18
177
183
181
184
182
188
185
88181
189
186
195
88190
194
191
193
192

PLATE 12

SPECIMEN M 9, SECTION L2-A; AT
0.02" FROM BACK; NITAL ETCH. X 500

SPECIMEN M 9, SECTION L2-B; AT
0.02" FROM BACK; NITAL ETCH. X 500

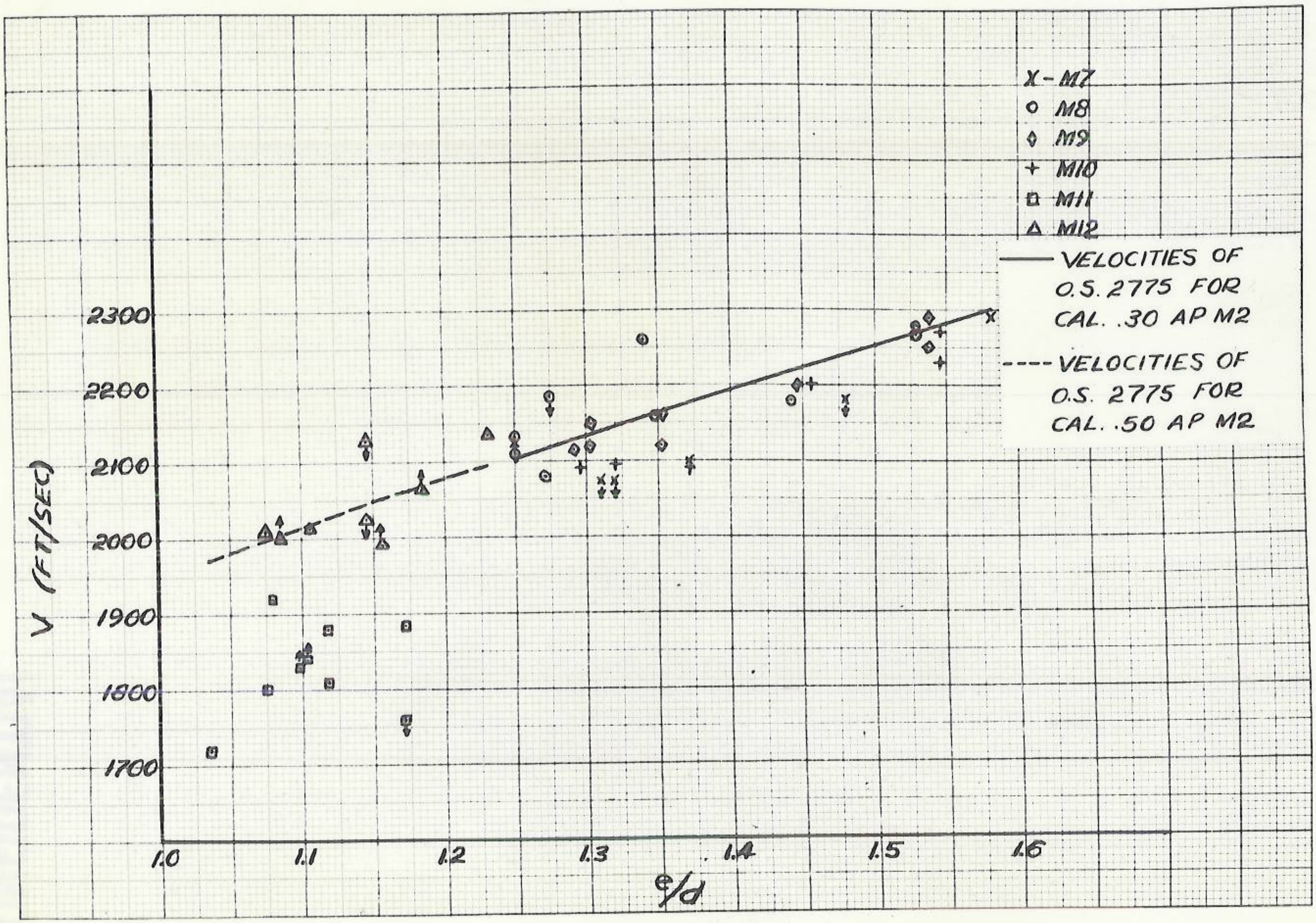

X - M7
o M8
◊ M9
+ M10
□ M11
Δ M12
—— VELOCITIES OF O.S. 2775 FOR CAL. .30 AP M2
---- VELOCITIES OF O.S. 2775 FOR CAL. .50 AP M2
V (FT/SEC)
2300
2200
2100
2000
1900
1800
1700
1.0
1.1
1.2
1.3
1.4
1.5
1.6
e/d

PLATE 14

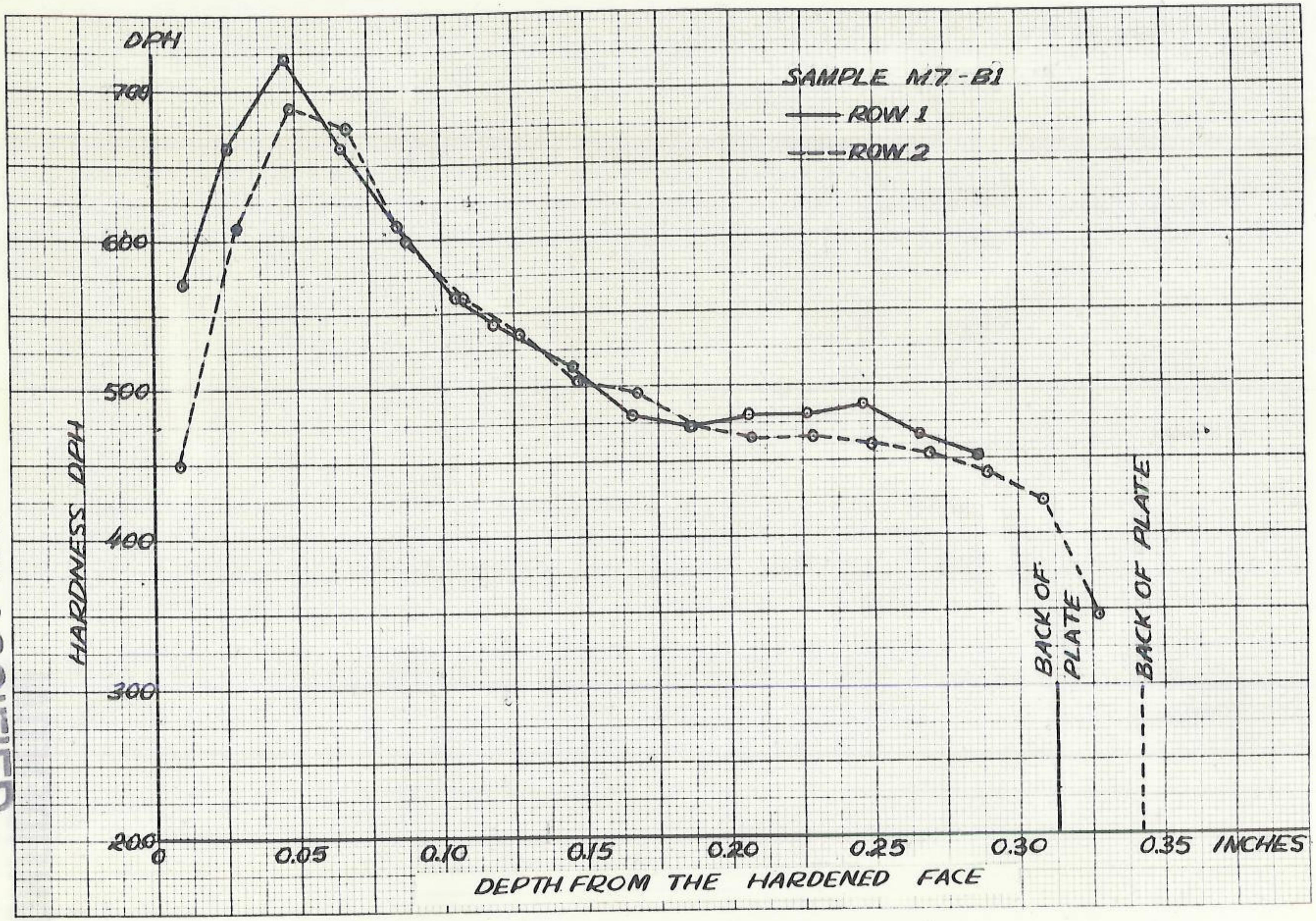

DPH
SAMPLE M7-B1
ROW 1
ROW 2
700
600
500
400
300
200
HARDNESS DPH
BACK OF PLATE
BACK OF PLATE
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
INCHES
DEPTH FROM THE HARDENED FACE

PLATE 15

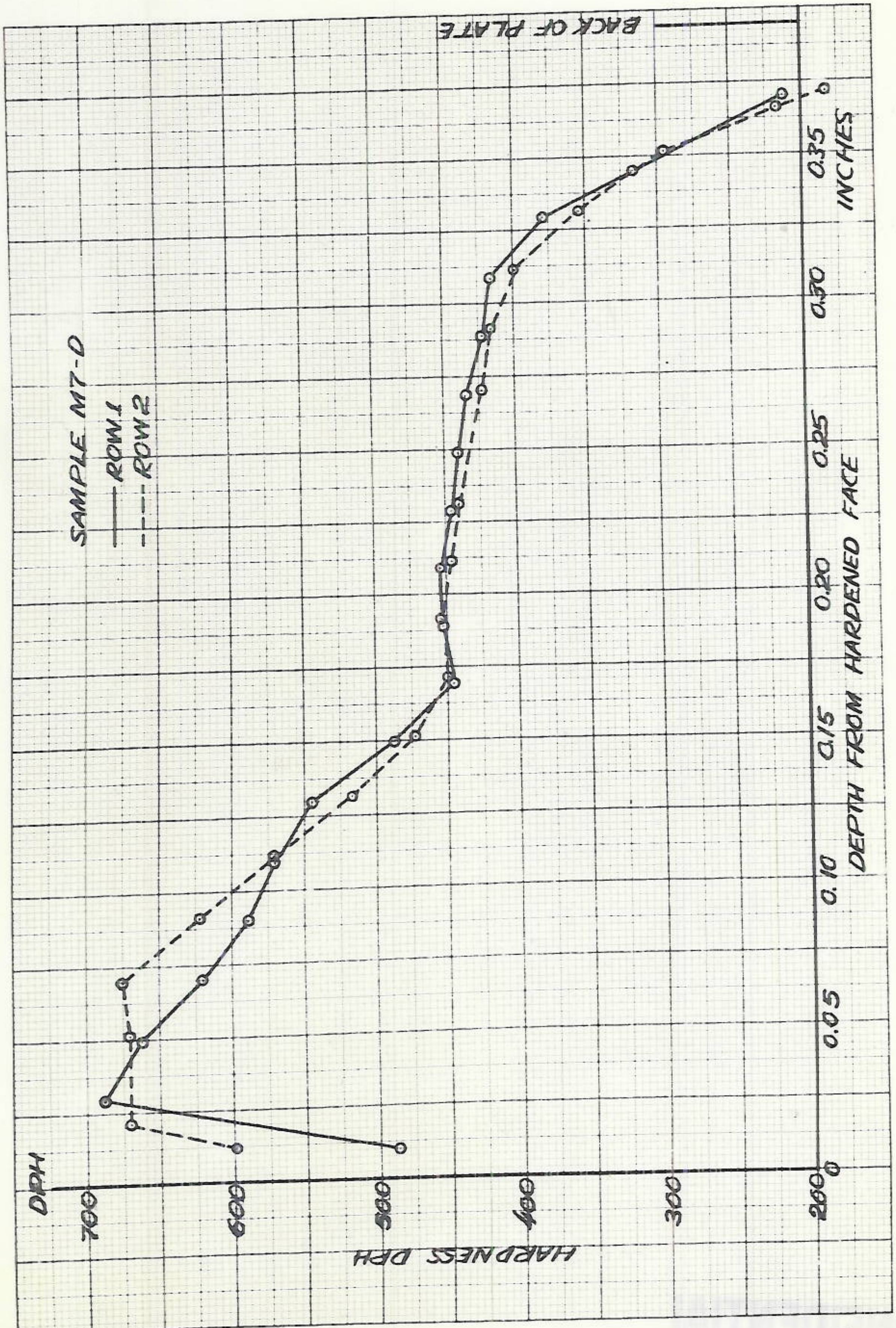

SAMPLE MT-D
ROW 1
ROW 2
BACK OF PLATE
DPH
700
600
500
400
300
200
HARDNESS DPH
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
DEPTH FROM HARDENED FACE
INCHES

PLATE 16

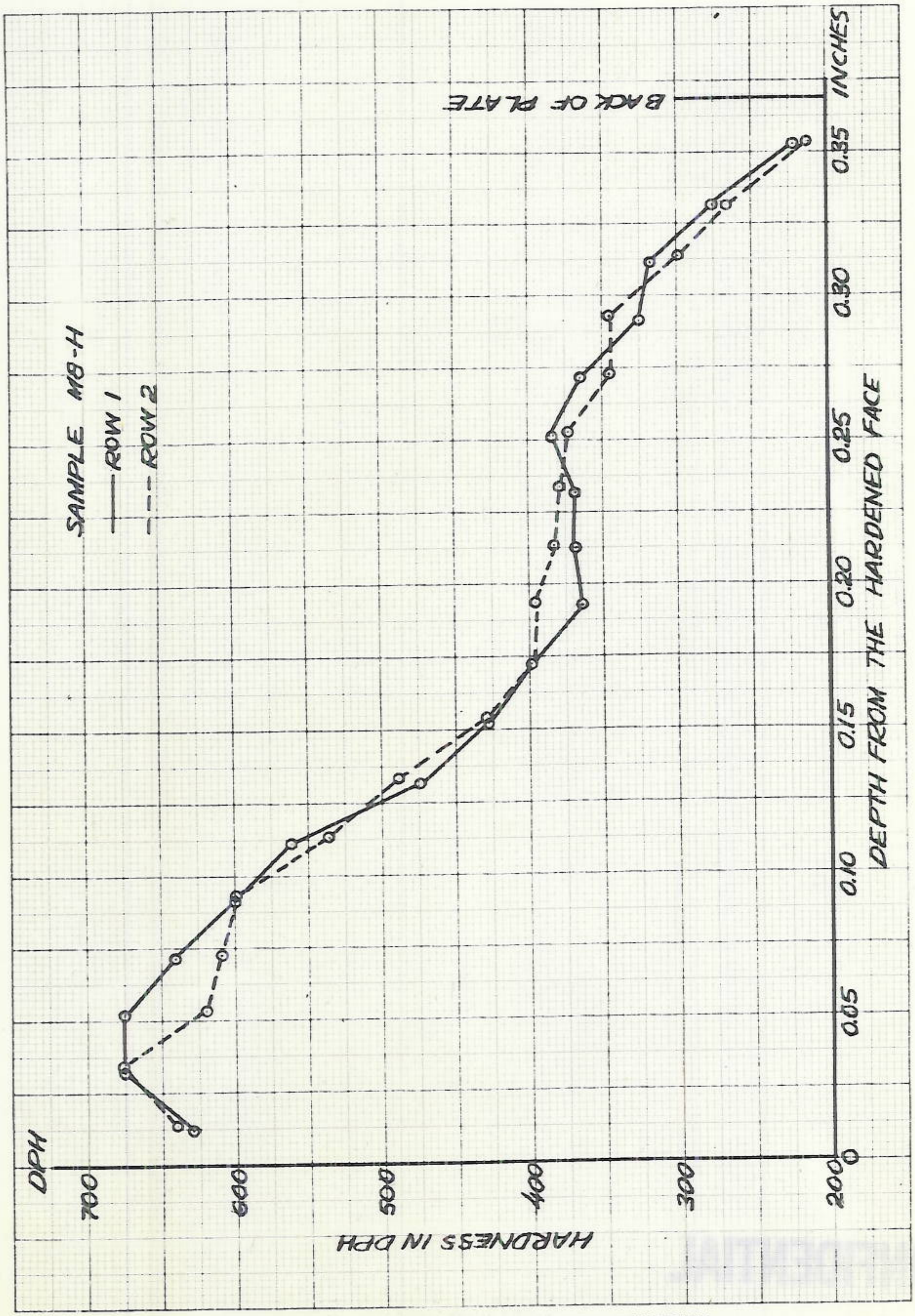

SAMPLE MB-H
ROW 1
ROW 2
BACK OF PLATE
DPH
700
600
500
400
300
200
HARDNESS IN DPH
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
INCHES
DEPTH FROM THE HARDENED FACE

PLATE 17

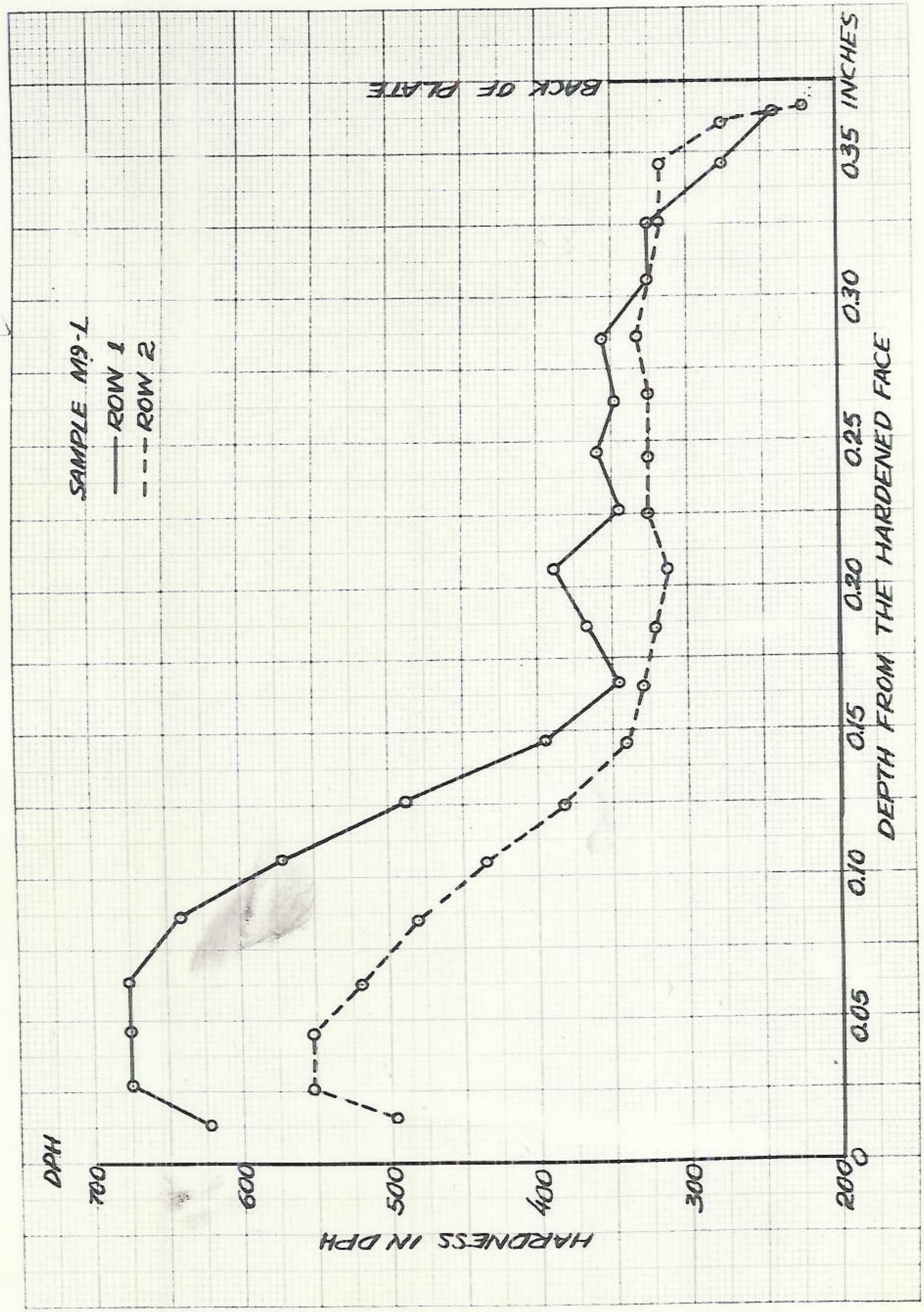

SAMPLE M9-L
ROW 1
ROW 2
BACK OF PLATE
DPH
700
600
500
400
300
200
HARDNESS IN DPH
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
INCHES
DEPTH FROM THE HARDENED FACE

PLATE 18

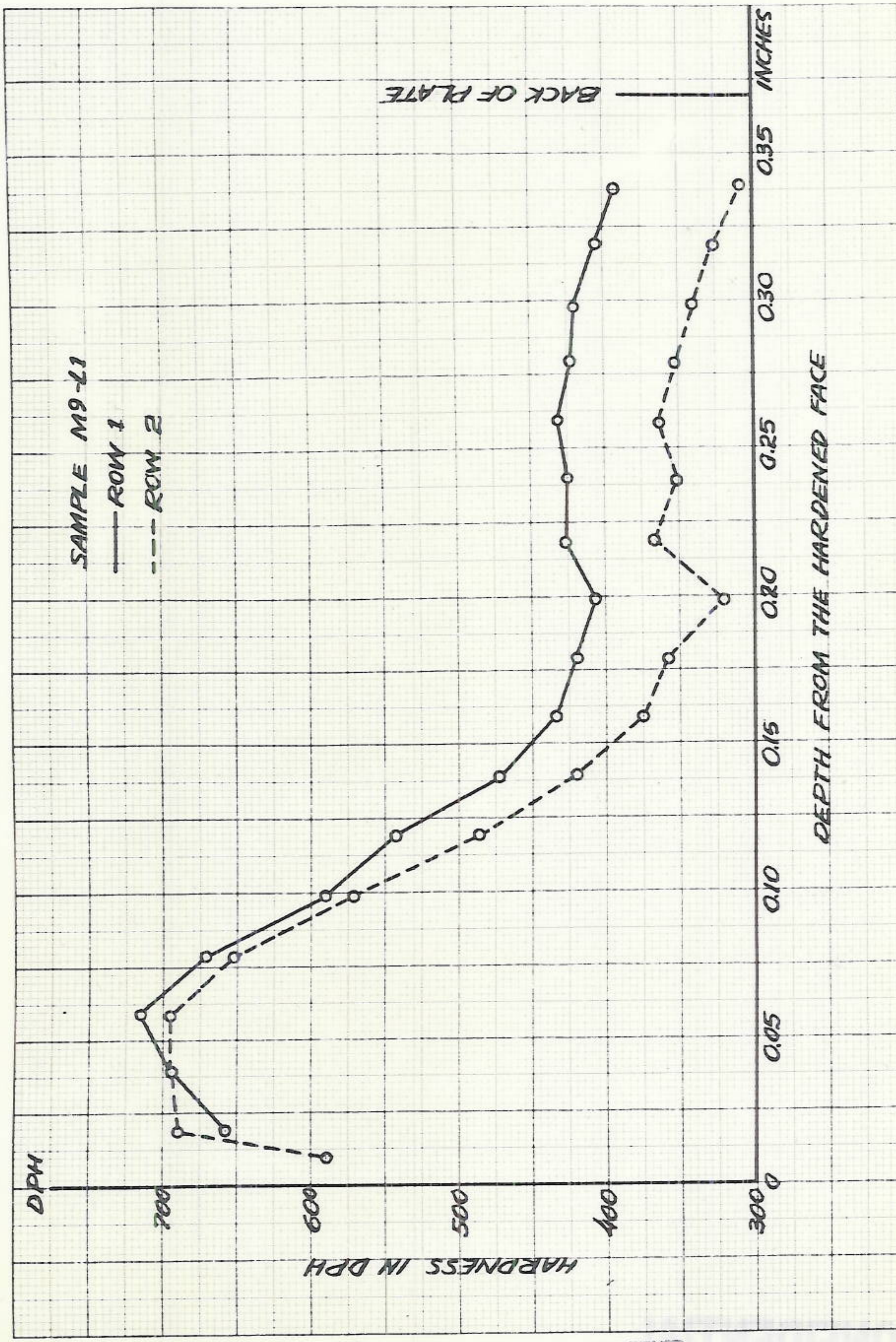

SAMPLE M9-L1
ROW 1
ROW 2
BACK OF PLATE
INCHES
DEPTH FROM THE HARDENED FACE
HARDNESS IN DPH
DPH
700
600
500
400
300
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35

 PLATE 19

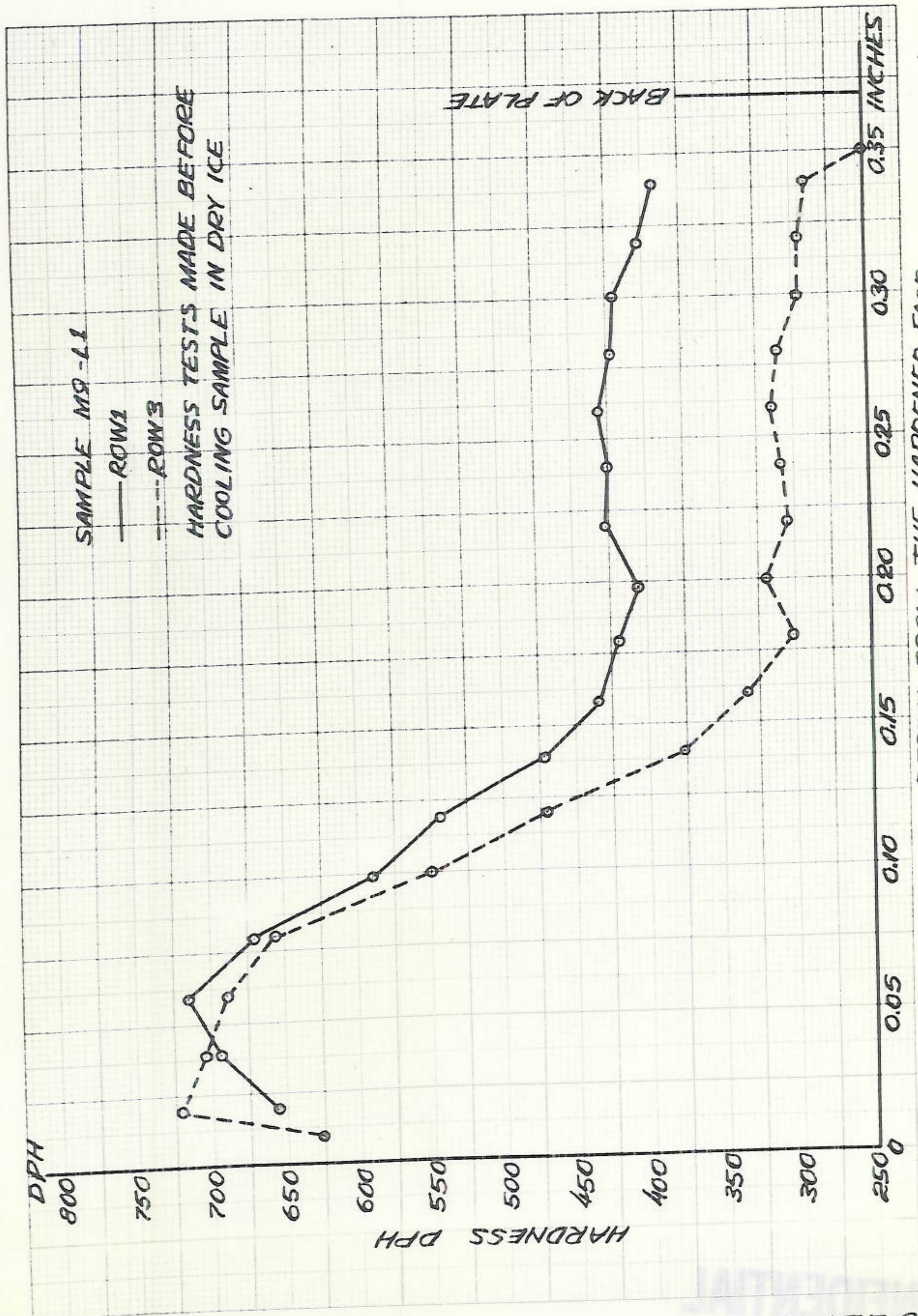
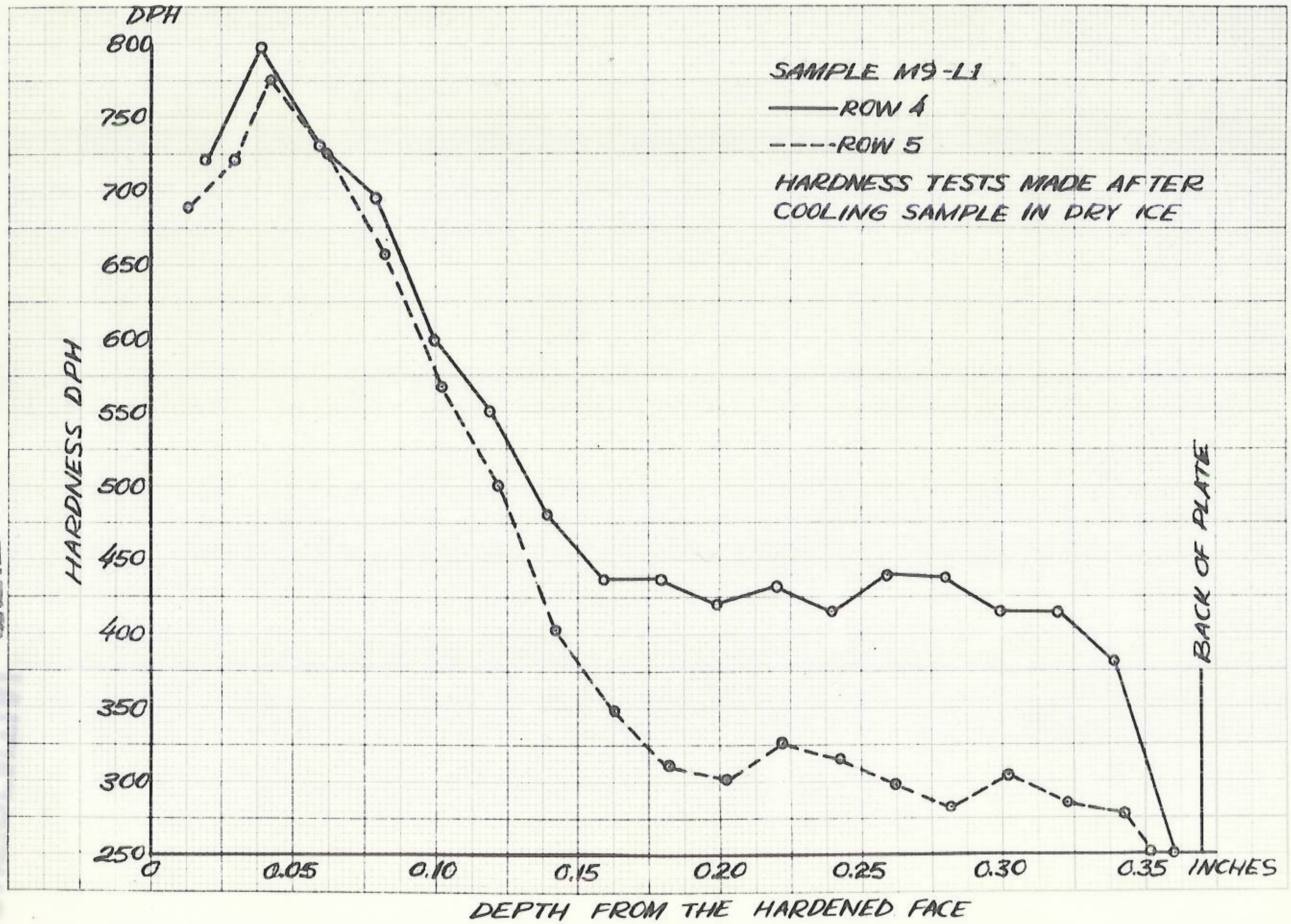

SAMPLE M9-11
—— ROW1
– – – ROW3
HARDNESS TESTS MADE BEFORE
COOLING SAMPLE IN DRY ICE
BACK OF PLATE
DPH
800
750
700
650
600
550
500
450
400
350
300
250
HARDNESS DPH
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35 INCHES
DEPTH FROM THE HARDENED FACE

PLATE 20



DPH
800
750
700
650
600
550
500
450
400
350
300
250
HARDNESS DPH
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
INCHES
DEPTH FROM THE HARDENED FACE
SAMPLE M9-L1
ROW 4
ROW 5
HARDNESS TESTS MADE AFTER
COOLING SAMPLE IN DRY ICE
BACK OF PLATE

PLATE 21

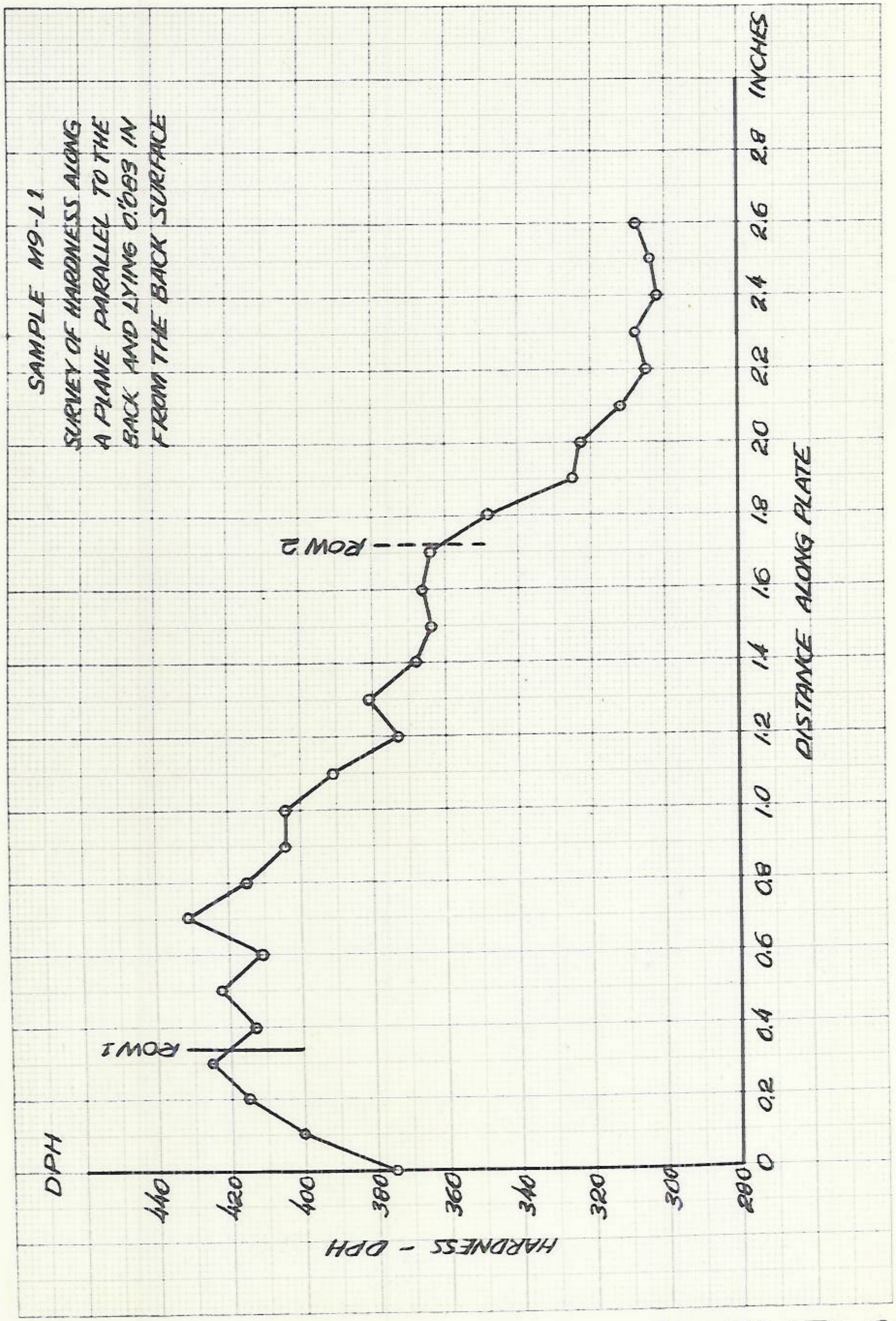
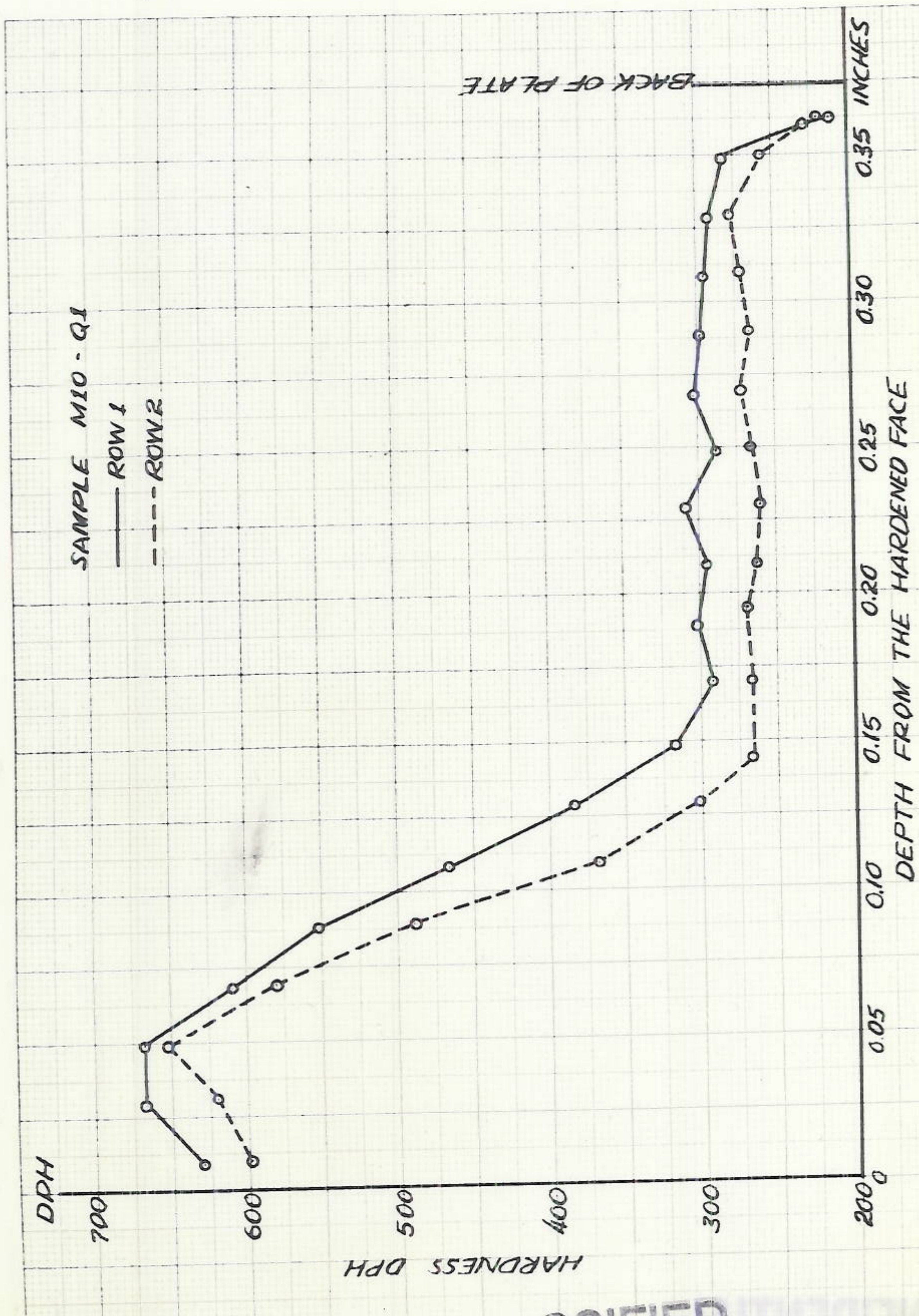

SAMPLE M9-L1
SURVEY OF HARDNESS ALONG A PLANE PARALLEL TO THE BACK AND LYING 0.083 IN FROM THE BACK SURFACE
ROW 1
ROW 2
DPH
HARDNESS - DPH
440
420
400
380
360
340
320
300
280
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
INCHES
DISTANCE ALONG PLATE

PLATE 22



SAMPLE M10 - Q1
ROW 1
ROW 2
BACK OF PLATE
DPH
700
600
500
400
300
200
HARDNESS DPH
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
INCHES
DEPTH FROM THE HARDENED FACE

PLATE 23

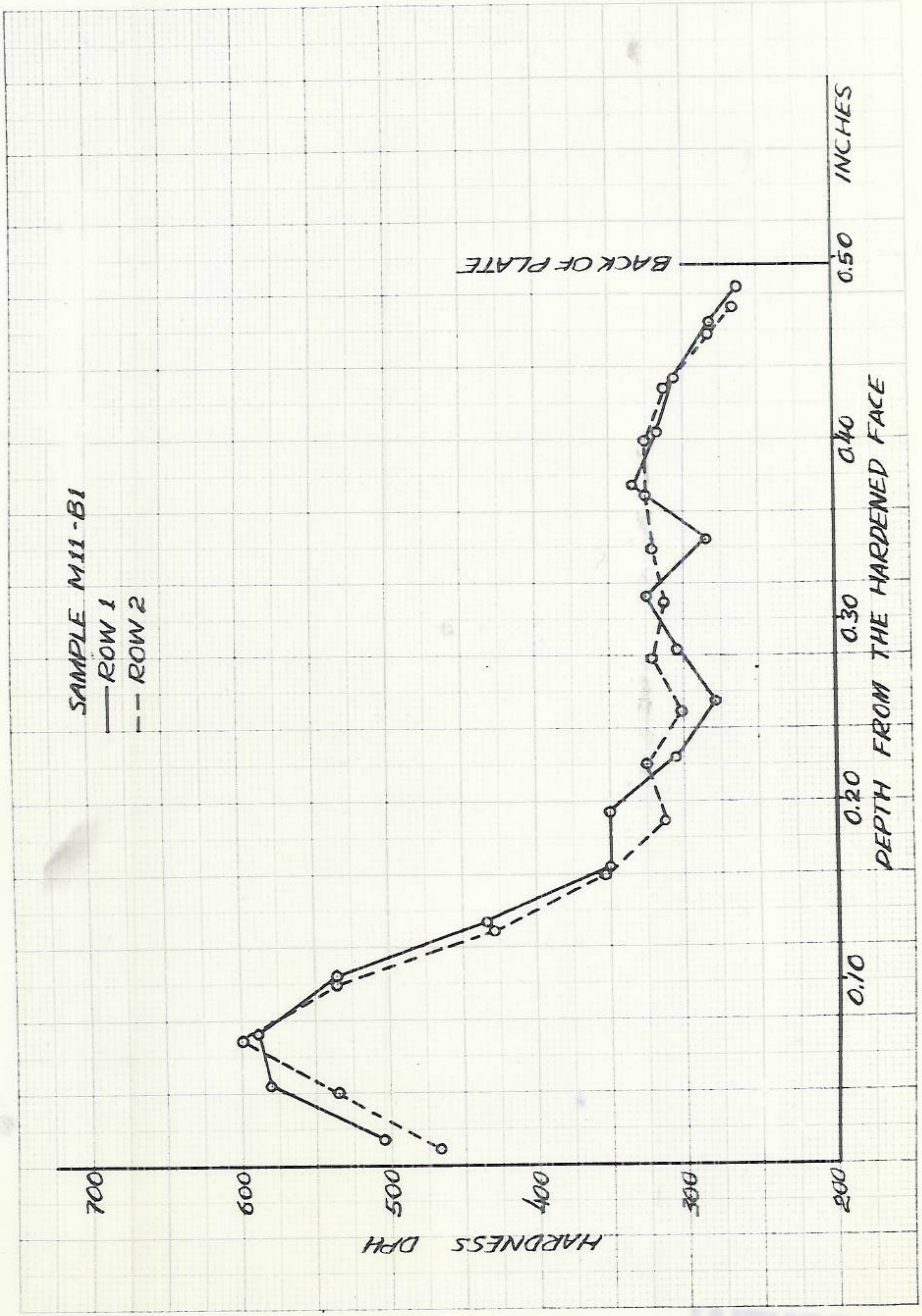

SAMPLE M11-B1
ROW 1
ROW 2
BACK OF PLATE
HARDNESS DPH
700
600
500
400
300
200
0.10
0.20
0.30
0.40
0.50
INCHES
DEPTH FROM THE HARDENED FACE

PLATE 24

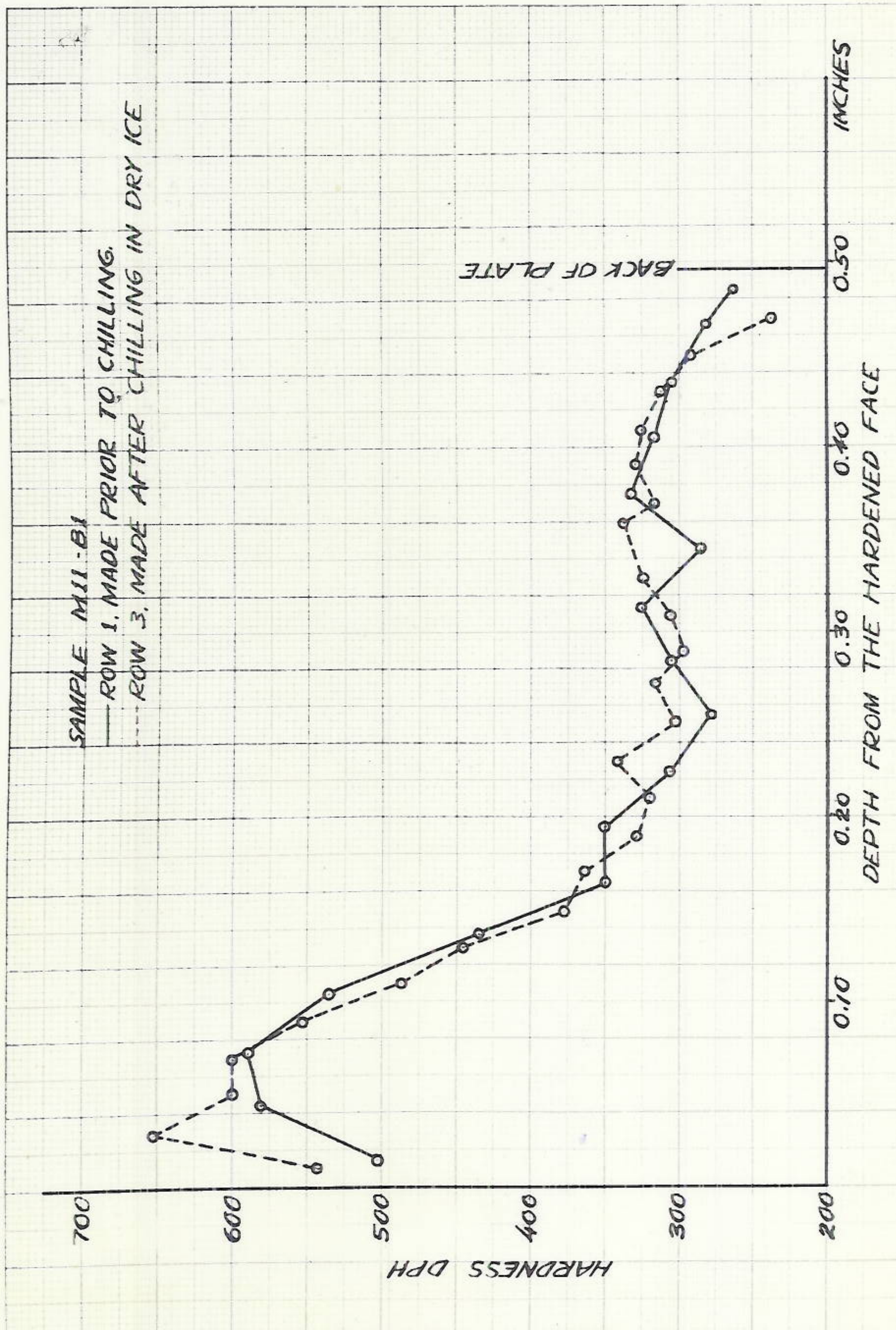

SAMPLE M11-B1
ROW 1, MADE PRIOR TO CHILLING.
ROW 3, MADE AFTER CHILLING IN DRY ICE
BACK OF PLATE
HARDNESS DPH
700
600
500
400
300
200
0.10
0.20
0.30
0.40
0.50
INCHES
DEPTH FROM THE HARDENED FACE

PLATE 25

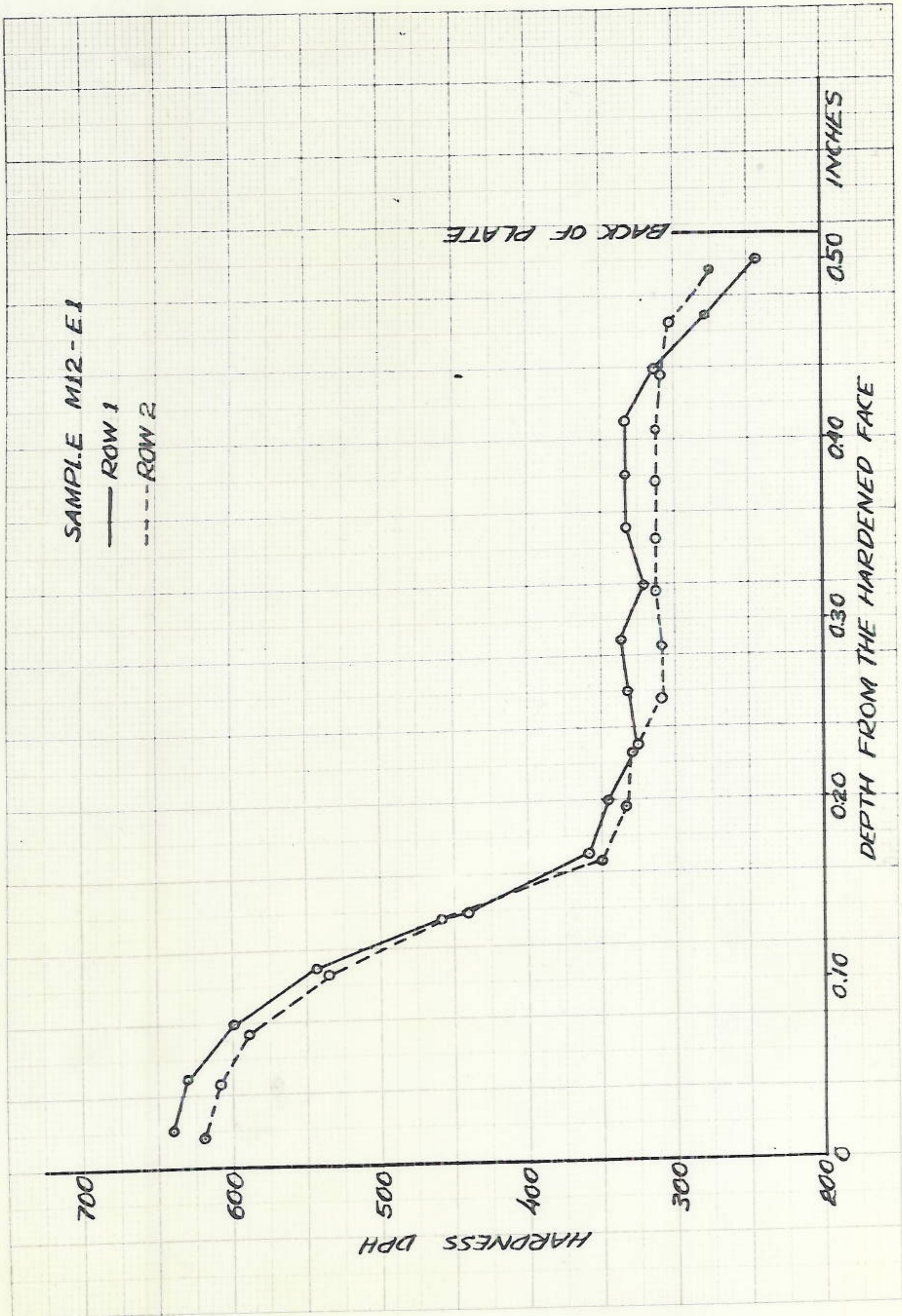

SAMPLE M12-E1
ROW 1
ROW 2
BACK OF PLATE
HARDNESS DPH
700
600
500
400
300
200
0
0.10
0.20
0.30
0.40
0.50
INCHES
DEPTH FROM THE HARDENED FACE

PLATE 26

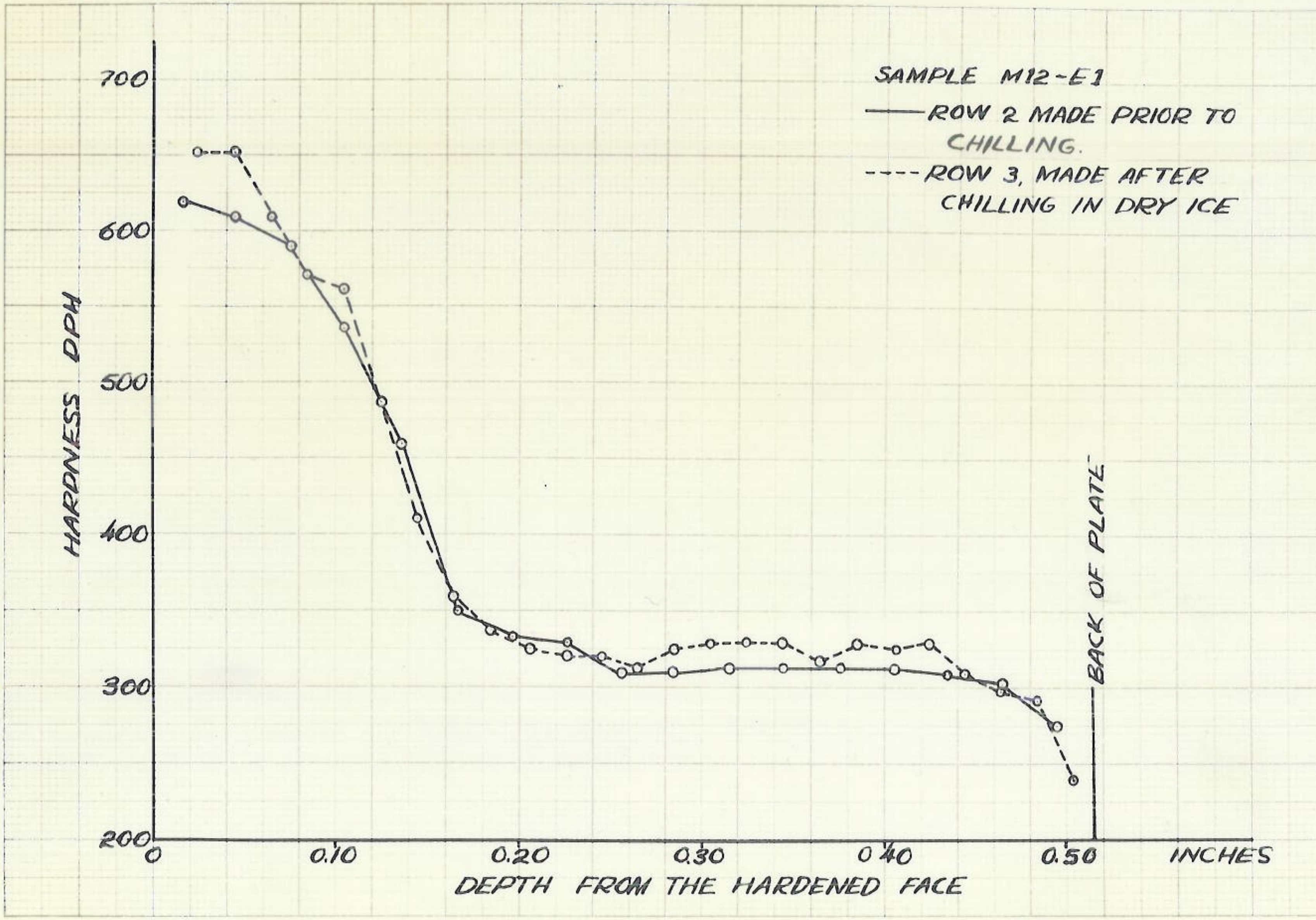

SAMPLE M12-E1
ROW 2 MADE PRIOR TO CHILLING.
ROW 3, MADE AFTER CHILLING IN DRY ICE
HARDNESS DPH
700
600
500
400
300
200
0
0.10
0.20
0.30
0.40
0.50
INCHES
DEPTH FROM THE HARDENED FACE
BACK OF PLATE

PLATE 27