BRL

REPORT NO. 641
October 1947

PENETRATION AND CRATER VOLUME IN VARIOUS KINDS OF ROCKS AS DEPENDENT ON CALIBER, MASS, AND STRIKING VELOCITY OF PROJECTILE

N. A. Tolch

A. V. Bushkovitch

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

BALLISTIC RESEARCH LABORATORIES

REPORT NO. 641

Penetration and Crater Volume in Various Kinds of Rocks as Dependent on Caliber, Mass, and Striking Velocity of Projectile

N. A. TOLCH

A. V. BUSHKOVITCH

16 OCTOBER 1947

ORDNANCE RESEARCH AND DEVELOPMENT DIVISION
OFFICE CHIEF OF ORDNANCE
PROJECT NO. TB3-0112E(TM2-9106)

ABERDEEN PROVING GROUND, MARYLAND

TABLE OF CONTENTS

BALLISTIC RESEARCH LABORATORIES

REPORT NO. 641

A.V. Bushkovitch/N.A. Tolch
Aberdeen Proving Ground, Md.
16 October 1947

PENETRATION AND CRATER VOLUME IN VARIOUS KINDS OF ROCKS AS DEPENDENT ON CALIBER, MASS, AND STRIKING VELOCITY OF PROJECTILE

ABSTRACT

Firings of caliber .50, 20mm, and 37mm A.P. projectiles were made on 4' x 4' x 3' blocks of granite, diabase, quartzite, oolitic limestone, and sandstone. The results of firing major caliber projectiles on limestone at Fort Knox, Kentucky, were obtained from the Armored Board. From the results of the firings, relations were deduced giving the depth of penetration and volume of crater as dependent on the caliber, mass, and striking velocity of projectile.

The observed penetrations were approximately inversely proportional to the cube roots of the compressive strengths of the rocks. Rock walls constructed of granite blocks were found to be inferior to massive monolithic granite due to the extensive spreading of cracks along the mortar bond. H.E. Type artillery shell with concrete piercing fuzes were observed to rupture on impact on a rock wall. Modified H.E. shell with thick cases, containing about 5% explosive, withstood impact on rock with deformation.

INTRODUCTION

In connection with the problem of the attack of rock fortifications, an extensive series of firings of artillery and small caliber projectiles on rocks of various kinds was made. The resulting data were reduced and utilized to formulate equations giving the penetration and crater volume as functions of weight, caliber, and striking velocity of projectile. From the equations, tables were computed giving penetrations and crater volumes of standard ammunition as functions of the range. Such tables were published in the form of Terminal Ballistic Data. The purpose of this report is to furnish the basis for the deduced laws of penetration and cratering.

SCOPE OF TESTS

The firings were made with small caliber projectiles so that rock blocks of transportable size could be used for targets. This plan permitted firing on a greater variety of kinds of rocks, and a greater speed in making the tests than would otherwise have been practicable. A range in caliber of guns was used so that the results could be scaled up to those of major calibers. Striking velocities were varied over as great a range as was practicable. Existing firings of major caliber projectiles on rocks were utilized for check points.

In line with this plan, Cal. .50 A.P. M2, 20mm A.P. M75, and 37mm A.P. M74 projectiles were fired against 4' x 4' x 3' blocks of the following rocks: Granite, Diabase, Quartzite, Oolitic Indiana Limestone, and Sandstone. Firings of major caliber projectiles were made on granite block walls and on limestone quarry walls.

The firings on the rock blocks, and the granite walls were made by the Arms and Ammunition Division of Aberdeen Proving Ground, while the firings in the limestone quarry were made by the Armored Board of Fort Knox.

RESULTS OF FIRINGS AGAINST ROCK BLOCKS AT A.P.G. AND NATURAL ROCK AT FORT KNOX

When a projectile strikes a rock face of large size relative to the projectile, the shape of the resulting crater is typically that of a cone, although large irregularities occur. If additional rounds are fired into the same crater, the first few rounds will deepen and widen the crater but the shape remains typically conical. If still more rounds are fired into the same crater, the rate of increase in diameter falls off and finally no further increase in diameter results. Additional shots will merely make a cylindrical hole in the rock of diameter somewhat larger than the projectile, a phenomenon which was called "drilling". If the projectile strikes a few calibers from an edge of a free face oriented parallel to the trajectory,shape of crater and volume of excavation will be greatly affected since the breakage of material will be facilitated by the additional free face. In view of this situation, the firings were made so that data would be obtained on the penetrations and crater volumes due to single rounds and to repeated rounds in the same crater, and on the effect on the volume of crater due to the proximity of an impact to an edge. The results of such firings appear in the following paragraphs.

A. Penetration and Crater Volumes due to Single Rounds.

The basic data on penetration and crater volumes due to single rounds are given in Table I*. This table gives the observed average penetration and crater volume of single rounds not impacting in the same crater for each condition of test.

In order that useful deductions may be made from the data, it is necessary to obtain formulas giving the penetration and volume as functions of the kind of rock, and the mass, caliber and striking velocity of the projectile. The data were fitted with formulas of the following types:

$$P = k_p \frac{W}{d^2} d^n \left(\frac{V}{1000}\right)^m \qquad (1)$$

$$S^{1/3} = k_s \frac{W}{d^2} d^n \left(\frac{V}{1000}\right)^m \qquad (2)$$

The explanation of the symbols and the units adopted are given in the following table.

P = Penetration, inches

k_p = Penetration constant

W = Weight of projectile, pounds

d = Projectile diameter; inches

V = Striking velocity, ft/sec

S = Crater volume, cubic inches

k_s = Volume constant

The form of Equation (1) was suggested from the results of previous and extensive firings on concrete slabs**. Equation (2) was made to agree with (1), dimensionally considered, by taking the cube root of the crater volume, and the same exponents, n and m in both (1) and (2).

Dependence of Penetration and Crater Volume on Striking Velocity $(V/1000)^m$

In order to determine the dependence of penetration and crater volume on striking velocity, the following procedure was adopted. Penetration was plotted against striking velocity for each projectile and each material, Plots 1 to 5. Likewise, crater volume to the 1/3 power was plotted against velocity, Plots 13 to 17. It appears that a satisfactory fit of the experimental points can be obtained by taking straight lines of slope unity. In view of this result, the constant m was taken equal to one in both (1) and (2).

* See also APG Firing Record No. P-38062

** R. A. Beth, Committee on Passive Protection Against Bombing, Interim Report No. 18.

TABLE I.

OBSERVED AVERAGE PENETRATIONS AND CRATER VOLUMES OF SINGLE ROUNDS OF A.P. PROJECTILES FIRED ON ROCKS

Material	No. Rds. in Average	Projectile, A.P.	Ave. Striking Vel., ft/sec.	Ave. Penet., inches	Ave. diam. of crater, inches	S, Ave. Vol. of crater, cu. in.	$S^{1/3}$
Granite	1	Cal. .50	911	1.1	1.5	.62	.85
	5	"	1229	1.1	2.7	2.24	1.3
	4	"	1821	1.4	4.9	8.58	2.0
	5	"	2728	2.0	6.1	19.8	2.7
	2	20mm	1155	1.7	4.9	10.5	2.2
	4	"	2001	3.2	7.5	47.8	3.6
	3	"	2734	4.1	15.0	240.	6.2
	1*	37mm	974	2.7	9.7	68.4	4.1
	1*	"	995	2.8	9.9	64.7	4.0
	1*	"	1973	5.1	Block	Broke	Up
	1*	"	2882	7.9	29.6	1810.	12.2
	*Data from Projectile Test Report, AD-P187						
Diabase	2	Cal. .50	1190	.84	2.9	1.90	1.2
	5	"	1798	1.4	4.4	7.10	1.9
	5	"	2671	2.0	7.6	30.8	3.1
	4	20mm	1147	1.7	8.6	33.3	3.2
	4	"	1971	2.8	9.2	62.0	4.0
	4	"	2618	3.7	15.0	215.	6.0
	5	37mm	1152	3.0	11.5	104.	4.7
	2	"	1885	4.5	19.7	459.	7.7
	1[a]	"	2641	8.0	27.5	1580.	11.6
	a Block split in half						
Quartzite	5	Cal. .50	1167	1.1	3.4	3.30	1.5
	5	"	1781	1.6	4.7	9.27	2.1
	5	"	2626	2.5	6.4	27.8	3.0
	5	20mm	1134	2.0	5.8	16.0	2.5
	5	"	1956	3.3	8.9	68.9	4.1
	1[b]	"	2638	4.5	12.4	180.	5.6
	b Block broke up						

TABLE I (Cont'd)

Material	No. Rds. in Average	Projectile A.P.	Ave. Striking Vel., ft/sec.	Ave. Penet., inches	Ave. diam. of crater, inches	S, Ave. Vol. crater, cu. in.	$S^{1/3}$
Limestone (Indiana)	5	Cal. .50	1214	1.5	4.0	6.76	1.9
	5	"	1776	2.5	6.2	25.8	2.9
	3	"	2663	4.3	7.8	68.9	4.1
	5	20mm	1142	2.5	8.0	41.7	3.5
	1	"	2000	5.5	16.9	410.	7.4
	4	37mm	1159	4.2	11.8	153.	5.3
	4	"	1925	7.6	9.1	142.	5.2
Sandstone	5	Cal. .50	1268	1.6	5.4	12.3	2.3
	4	"	1779	2.7	9.3	62.4	4.0
	5	"	2650	3.8	10.4	107.	4.7
	5	20mm	1147	2.6	9.8	66.2	4.0
	4	"	1977	4.9	13.7	195.	5.8
	1	37mm	1190	4.5	10.9	141.	5.2
Limestone (Warsaw)	1	75mm M61	2040	9.5	30	2250	13.1
	1	75mm M72	2030	12	32	3110	14.7
	1	76mm M62	2600	11	34	3290	15.0
	1	90mm M82	2700	19	40	7950	20.0
	1	90mm M77	2700	14	40	5880	18.0
Limestone (St. Louis)	1	75mm M72	2030	19	44	9640	21.3
	1	75mm M61	2030	15	48	9050	20.8
	1	76mm M62	2600	28	54	21400	27.8
	1	90mm M77	2700	36	60	33900	32.4
	1	90mm M82	2650	24	60	22600	28.3

Scale Factor, d^n

The quantity d^n is the so-called scale factor since in its absence (n = 0) penetration should be proportional to caliber for geometrically similar projectiles. The following procedure was used in determining n from the observed data.

In equation (1), let

$$K' = k_p \frac{W}{d^2} d^n$$

Hence, $P = K' \left(\frac{V}{1000}\right)$

Likewise in Equation (2), let

$$K'' = k_s \left(\frac{W}{d^2}\right) d^n$$

and $S^{1/3} = K'' \left(\frac{V}{1000}\right)$

The quantities k'/W for different calibers but the same rock were plotted against the caliber, d, and a straight line was drawn through the experimental points, or as nearly as possible to them, Plots 6 to 12. Similarly, k''/W was plotted against d, Plots 18 to 24. From the slopes of the straight lines it was possible to determine the values of the constant n. The results are given in Tables II and III.

Examination of Tables II and III shows that the exponent n of the scale factor varies widely from material to material. Since there is no good ground for expecting such large variations in the scale factor for the various rocks, the variations must be attributed to the smallness of the sample and to differences in the circumstances of the impact, such as orientation with respect to the cleavage planes of the rock block, and lack of homogeneity in the block. It thus appears preferable to select an average value for the exponent n, assuming therefore that the scale factor does not vary from material to material.

In averaging together the values of n given in Table II, the values for St. Louis and Warsaw limestone, obtained from firings at Fort Knox, were given only half as much weight as the other values, since the observations were much fewer in number. The result is .11. This is somewhat lower than the value of .2 adopted by Beth for concrete on the basis of extensive firings. As a compromise between these results, the value n = 1/6 was adopted for equation (1). Although the value of n obtained from Table III is somewhat lower, -.03, it was thought desirable from dimensional considerations to use the same value of n for equation (2). Thus, n = 1/6 was adopted for both equations (1) and (2).

Determination of Penetration and Volume Constants, k_p and k_s

Taking m = 1, and n = 1/6, the observed penetrations were substituted in equation (1), crater volumes in (2), thus giving values of k_p and k_s. The results for each rock, projectile, and velocity are listed in Table IV. The constants for each kind of rock were then averaged together. The average results are summarized in Table V.

TABLE II

k' and n computed from penetration data.

(Single Round)

Projectile	k'	n
	A. GRANITE	
Cal. .50	.789	.17
20mm	1.525	"
37mm	2.66	"
	B. DIABASE	
Cal. .50	.745	.14
20mm	1.434	"
37mm	2.49	"
	C. QUARTZITE	
Cal. .50	.926	.01
20mm	1.706	"
37mm	-	-
	D. LIMESTONE (INDIANA)	
Projectile	k'	n
Cal. .50	1.43	-.04
20mm	2.44	"
37mm	3.79	"
	E. SANDSTONE	
Cal. .50	1.42	-.13
20mm	2.39	"
37mm		-
	F. LIMESTONE (WARSAW)	
75 & 76mm	5.00 (AV.)	.44
90mm	6.19 (AV.)	"
	G. LIMESTONE (ST. LOUIS)	
75 & 76mm	9.36	.53
90mm	11.36	.53

TABLE III

k" and n computed from crater data.

(Single Round).

Projectile	k"	n
	A. GRANITE	
Cal. .50	.992	.32
20mm	1.986	"
37mm	4.153	"
	B. DIABASE	
Cal. .50	1.093	.00
20mm	2.344	"
37mm	4.195	"
	C. QUARTZITE	
Cal. .50	1.202	-.04
20mm	2.153	"
37mm	-	-
	D. LIMESTONE (INDIANA)	
Cal. .50	1.586	-.19
20mm	3.359	"
37mm	3.537	"
	E. SANDSTONE	
Cal. .50	1.939	-.14
20mm	3.216	"
37mm	-	-
	F. LIMESTONE (WARSAW)	
75 & 76mm	6.58 (Ave.)	-.18
90mm	7.12 (Ave.)	"
	G. LIMESTONE (ST. LOUIS)	
75 & 76mm	10.69 (Ave.)	-.16
90mm	11.51 (Ave.)	"

TABLE IV

Penetration and Crater Volume Constants

Target Material	No. Rds. Fired	Projectile	Striking Velocity ft/sec.	P Penetration, Inches	$S^{1/3}$ (Crater Volume)$^{1/3}$ Inches$^{1/3}$	k_p Penetration Constant	k_s Volume Constant
Granite	5	Cal. .50	1229	1.15	1.31	3.41	3.87
	4	Cal. .50	1821	1.36	2.05	2.72	4.09
	5	Cal. .50	2726	2.00	2.70	2.67	3.61
	2	20 mm	1155	1.69	2.19	2.59	3.36
	4	20 mm	2001	3.25	3.63	2.87	3.21
	3	20 mm	2734	4.08	6.22	2.64	4.02
	1	37 mm	974	2.75	4.09	2.94	4.36
	1	37 mm	995	2.50	4.01	2.61	4.19
	1	37 mm	2882	5.13	12.19	1.85	4.40
						2.70	3.90
Diabase	2	Cal. .50	1190	.84	1.24	2.57	3.79
	5	Cal. .50	1798	1.37	1.92	2.77	3.89
	5	Cal. .50	2671	2.05	3.14	2.79	4.28
	4	20 mm	1147	1.72	3.22	2.65	4.96
	4	20 mm	1971	2.77	3.96	2.49	3.56
	4	20 mm	2618	3.66	5.99	2.47	4.05
	5	37 mm	1152	2.99	4.71	2.70	4.25
	2	37 mm	1885	4.50	7.72	2.48	4.25
	1	37 mm	2641	8.00	11.66	3.15	4.59
						2.67	4.18
Quartzite	5	Cal. .50	1167	1.07	1.49	3.33	4.64
	5	Cal. .50	1781	1.58	2.10	3.23	4.29
	5	Cal. .50	2626	2.55	3.03	3.53	4.20
	5	20 mm	1134	1.96	2.52	3.06	3.93
	5	20 mm	1956	3.29	4.10	2.97	3.71
	1	20 mm	2638	4.50	5.65	3.02	3.79
						3.19	4.09

TABLE IV (Cont'd)

Target Material	No. Rds. Fired	Pro-jectile	Striking Velocity ft/sec.	P Penetration Inches	$S^{1/3}$ (Crater Volume)$^{1/3}$, Inches$^{1/3}$	k_p Penetration Constant	k_s Volume Constant
Limestone (Indiana)	5	Cal. .50	1214	1.55	1.89	4.65	5.67
	5	Cal. .50	1776	2.52	2.95	5.16	6.06
	3	Cal. .50	2663	4.29	4.10	5.86	5.61
	5	20 mm	1142	2.57	3.47	3.98	5.39
	1	20 mm	2000	5.50	7.43	4.87	6.58
	4	37 mm	1159	4.22	5.35	3.79	4.81
	4	37 mm	1925	7.59	5.21	4.10	2.82*
	*Excluded from average					4.63	5.69
Sandstone	5	Cal. .50	1268	1.61	2.31	4.62	6.62
	4	Cal. .50	1779	2.75	3.97	5.63	8.12
	5	Cal. .50	2650	3.82	4.75	5.25	6.53
	5	20 mm	1147	2.62	4.04	4.05	6.24
	4	20 mm	1977	4.94	5.80	4.42	5.19
	1	37 mm	1190	4.50	5.20	3.93	4.55
						4.65	6.21
Limestone (Warsaw)	1	75mm APC	2020	9.5	13.08	2.29	3.16
	1	75mm AP	1990	12	14.76	3.14	3.87
	1	76mm APC	2575	11	15.00	2.07	3.55
	1	90mm APC	2680	19	19.92	3.00	3.15
	1	90mm AP	2650	14	18.00	2.30	2.95
						2.56	3.34
Limestone (St. Louis)	1	75mm APC	1980	15	21.24	3.70	5.59
	1	75mm AP	1975	19	20.88	5.00	5.15
	1	76mm APC	2570	28	27.72	5.27	5.23
	1	90mm APC	2650	24	32.40	3.86	5.31
	1	90mm AP	2625	36	28.32	5.91	4.56
						4.75	5.17

In Table V, the values for Granite, Diabase, and Warsaw Limestone were averaged together because they are not significantly different at the 5% level of significance. For convenience, this group was designated as hard rocks. Similarly, the values for Indiana Limestone, Sandstone, and St. Louis Limestone were averaged together and designated as soft rocks. St. Louis Limestone, although performing like a soft rock as regards penetration and cratering, is not essentially a soft rock as will appear in a later paragraph. Since the k_p for Quartzite seems not to belong to either group, statistically considered, the values for this rock were kept separate.

Table V. Summary of Average Penetration and Volume Constants

Kind of Rock	k_p	k_s
Hard Rock;		
Granite	2.70	3.90
Diabase	2.67	4.18
Limestone (Warsaw)	2.56*	3.34*
Average	2.7	3.9
Quartzite	3.2	4.1
Soft Rock:		
Limestone (Indiana)	4.63	5.69
Sandstone	4.65	6.21
Limestone (St. Louis)	4.75*	5.17*
Average	4.7	5.8

* Given 1/2 weight in averaging.

Final Penetration and Crater Formulas

From the results given in the preceding paragraphs, the penetration and crater formulas for single rounds are as follows:

$$P = k_p \frac{W}{d^2} d^{1/6} \left(\frac{V}{1000}\right) \qquad (1)$$

$$S^{1/3} = k_s \frac{W}{d^2} d^{1/6} \left(\frac{V}{1000}\right) \qquad (2)$$

The values of the constants are as follows:

Target Material	k_p	k_s
Hard Rock	2.7	3.9
Soft Rock	4.7	5.8

TABLE VI

Penetrations and Crater Volumes in Rocks due to Repeated Impacts of A.P. Projectiles

Material	No. Rd's in same Crater	Pro-jectile (A.P.)	Ave Striking Velocity ft/sec.	Ave Penet. inches	Ave diam. of Crater inches	Vol. of Crater cu. in.
Granite	1	cal..50	1148	1.1	2.9	2.45
	3			1.6	4.3	7.59
	5			1.9	4.5	10.3
	9			2.4	7.5	35.0
	1	"	1662	1.6	4.2	7.17
	3			1.9	6.4	20.7
	6			3.5	6.7	41.7
	1	"	2600	2.2	6.7	26.8
	2			2.4	8.5	46.1
	3			4.2	11.2	141.
	1	20 mm	1166	1.9	6.7	23.1
	3			3.7	8.7	73.9
	5			4.9	15.4	302.
	1	"	1965	2.9	11.0	93.1
	2			4.9	11.5	171.
	1	"	1955	3.4	9.2	75.7
	2			5.0	17.5	401.
	3			6.2	23.0	865.
Diabase	1	cal..50	1218	1.0	3.2	2.76
	3			1.4	3.3	3.98
	7			1.9	3.5	6.03
	9			2.2	6.9	27.1
	1	"	1604	1.4	2.9	3.13
	3			1.9	5.7	16.3
	5			2.3	6.0	21.8
	1	"	1798	.75	1.2	.31
	2			1.1	3.9	4.43
	1	"	2635	1.7	7.0	22.4
	3			3.2	12.0	120.
	6			4.7	18.5	425.
	1	20 mm	1141	1.7	9.5	39.9
	3			3.1	9.5	73.9
	7			4.4	10.6	130.
	1	"	1964	2.9	10.1	77.2
	3			5.7	29.0	1260.
	6			8.5	33.0	2420.

TABLE VI. (Cont'd.)

Material	No. Rd's in same Crater	Pro-jectile (A.P.)	Ave. Striking Velocity ft/sec.	Ave. Penet. inches	Ave. diam. of Crater inches	Vol. of Crater cu. in.
Quartzite	1	20 mm	1154	2.2	8.0	37.7
	2			3.4	8.5	63.8
	1	"	1946	3.0	10.0	78.5
	2			5.4	14.5	296.
	3			6.5	18.7	598.
	1	"	2658	4.4	16.7	321.
	2	"		7.7	19.4	762.
Limestone (Indiana)	1	20 mm	1162	2.6	8.0	44.0
	2			3.4	13.0	150.
	3			3.7	13.2	157.
	4			4.9	14.8	280.
	1	"	2010	5.0	9.2	112.
	2			8.0	19.0	756.
	3			8.7	21.0	1010.
Sandstone	1	"	1175	2.4	9.4	56.1
	2			3.7	9.5	98.6
	1	"	2006	5.0	15.5	314.
	2			9.2	17.2	721.
	1	"	2713	8.0	19.5	796.
	2			11.2	20.1	1190.
	1	37 mm	1174	4.0	15.1	238.
	2			7.0	21.2	823.
	3			9.7	21.8	1210.
Limestone (Warsaw)	1	75mmM31	2040	9.5	30	2250
	5			34	36	11400
	16			42	50	27300
	1	75mmM72	2030	12	32	3110
	6			48	52	33700
	1	76mmM62	2600	11	34	3290
	5			51	42	23500
Limestone (Warsaw)	1	90mmM82	2700	19	40	7950
	5			(36 (22	66 Cone) 24 Cyl.)	49300
	30			(36 (130	66 Cone) 24 Cyl.)	97000
	1	90mmM77	2700	14	40	5880
	5			(30 (45	50 Cone) 12 Cyl.)	24500
	15			(45 (80	50 Cone) 16 Cyl.)	45500
	17	75mmM72	2030	(28 (72	40 Cone) 12 Cyl.)	19900

CRATER VOLUME IN REPEATED ROUNDS

The basic data on the effect of repeated impacts on crater volume are given in Table VI. Since it is reasonable to expect that rounds following the first and striking in the same crater will excavate greater quantities of the already loosened material than was the case in the first round, the results were reduced using the formula $S_n = S_1 n^x$, where n is the number of rounds, S_n the crater volume after n rounds and S_1 the crater volume after the first round. Average values of the exponent x for each material are given in Table VII.

TABLE VII Values of Exponent x in Equation $S_n = S_1 n^x$.

Material	x
Granite	1.4
Diabase	1.7
Quartzite	1.3
St. Louis & Warsaw Limestone	.68
Indiana Limestone	1.7
Sandstone	.98
Average	1.3

In the case of the repeated round effect there does not appear to be any difference in the exponent between the hard and the soft rocks. Hence the value of 1.3 may be taken as an average value for all rocks, giving as the final equation for repeated round effect

$$S_n = S_1 n^{1.3}; n \leq 5 \quad (3)$$

The values of S_n given in Table VI have been plotted against n in Plots 25 to 29. The straight lines are those given by eq. (3). It will be noted that the lines fit the data fairly well in some cases, and very poorly in others. However, the experimental points are so distributed that no one formula could be expected to fit in all cases. The best that can be hoped for on the basis of the available data, is to give formulas which will, on the average, predict the correct order of magnitude, although there will be considerable dispersion in the results. Due to the phenomenon of drilling, the equation should not be expected to hold when the number of rounds exceeds about 5.

D. Edge Effect.

An accurate evaluation of the edge effect, i.e. the effect on the volume of the crater due to its proximity to an edge of the block, is even more difficult than that of the other aspects of the impact of projectiles on rock targets. This is chiefly because the result is influenced even more than in the case of penetration and crater volume by the local circumstances of the impact, such as presence of flaws which facilitate the formation of cracks; orientation with respect to cleavage planes, etc. As a result, very extensive firings are necessary; because of the difficulties mentioned above, only a modest proportion of the data obtained were usable for estimating the edge effect. Those results which are usable have been collected in Table VIII. This table gives the results of firings in which the impacts were either 5 or 10 calibers from an edge. The observed crater volume is given together with the value computed using formulas (2) and (3) on the assumption of no edge effect; together with the ratio of the observed value to the computed one.

Examination of Table VIII shows a certain amount of consistency in the results for Cal. .50 projectiles against granite and diabase. The edge-effect ratio (volume with edge effect/volume without edge effect) appears to be about 1.7 for impacts 10 calibers from an edge while it is only about .6 for impacts 5 calibers from an edge. However much larger values are also observed (up to 5.2) as in the case of cal. .50 projectiles on quartzite and 20mm projectiles on Granite.

In so far as conclusions may be drawn from the amount of data available, the edge effect may be described as follows: if no extensive cracking appears, the edge effect ratio is less than 1 (about .7) for impacts 5 calibers from an edge. This means simply that the impact is too close to the edge for the formation of a complete crater. When the impact is sufficiently far from an edge for the complete crater to form (e.g. 10 calibers) the edge-effect ratio is greater than 1 (about 1.7); however, it may take several rounds for the crater to break to the edge. Also, it should be kept in mind that the above represents what might be termed normal behavior. If extensive cracking should take place, the edge effect ratio may be much higher, values as high as 5.2 having been observed.

E. Compressive Strength Vs. Penetration.

In order to obtain information on the relation between compressive strength and resistance to penetration, samples of each kind of rock fired on at Aberdeen were sent to the National Bureau of Standards for test. Samples of Warsaw and St. Louis Limestone, which were fired on at Fort Knox had been tested by the U.S. Geological Survey. The strength tests were made on 2" cylinders, two trials for each kind of rock. The following table gives the results of the compressive strength tests, and also the penetration constants:

Kind of Rock	Source	Compressive Strength lbs./sq. in.	Penetration Constant k
Diabase	Birdsboro, Pa.	30,900	2.7
Granite	Mt. Airy, N.C.	22,600	2.7
Quartzite	Nashville, Tenn.	25,600	3.2
Warsaw Limestone	Fort Knox, Ky.	20,000	2.6
St. Louis Limestone	Fort Knox, Ky.	19,500	4.7
Oolitic Limestone	Indiana	4,850	4.6
Sandstone	Cleveland, Ohio	6,000	4.6

If the results for St. Louis Limestone are excluded, it appears that the following relation holds approximately:

Penetration α $1/(\text{comp. strength})^{1/3}$

TABLE VIII

EDGE EFFECT

A. CAL. .50

Material	No. Rds.	Dist. from Edge, calibers	Velocity	Vol w/o Edge Effect (computed) cu. in.	Vol w/edge effect (observed) cu. in.	Vol w/edge effect / Vol w/o edge effect
Granite	3	10	1783	31.4	43	1.4
	2	"	2601	57.5	131	2.3
	4	"	2628	145.9	196	1.3
	5	"	2614	192.0	331	1.7
	1	5	2626	24.0	15	.63
	2	"	2626	59.0	43	.73
	3	"	2610	98.4	69	.70
	*2	"	1783	18.5	69*	3.7*
	*Hit near corner					
Diabase	1	5	2726	26.9	12	.45
	1	"	2617	23.8	14	.59
	1	"	2655	24.8	18	.73
Quartzite	1	5	1799	7.72	34.5	4.5
	1	"	2629	24.11	88	3.6

B. 20 MM

Material	No. Rds.	Dist. from Edge, calibers	Velocity	Vol w/o Edge Effect (computed) cu. in.	Vol w/edge effect (observed) cu. in.	Vol w/edge effect / Vol w/o edge effect
Granite	1	5	1156	17.7	93	5.2
	1	10	2738	237	336	1.4

There is evidence that the relation between compressive strength and penetration is modified by the degree of weathering and fissuring in the natural rock formations. For example, the St. Louis bed, which lies directly above and in contact with the Warsaw, is fissured to such an extent that it was difficult to procure perfect specimens large enough for a compressive strength test. When measured on small specimens, the observed compressive strengths of the St. Louis and Warsaw beds were practically equal. However, it may be observed that the penetrations into the St. Louis bed were appreciably greater than those into the Warsaw. It is supposed that the fissuring of the St. Louis bed facilitated penetration into it.

FIRINGS INTO GRANITE BLOCK WALLS

There were available for the firings 3 granite block walls; which were to be utilized for large scale checks of the penetration constants determined by the firings of cal .50, 20mm, and 37mm projectiles. It turned out, however, that the walls did not behave as monoliths when subjected to impacts with projectiles. In view of this situation, the firings did not yield useful information on the penetrations into rock in the massive monolithic state. The firings did, however, yield useful data on the relative performance of various types of projectiles and on the structural behavior of a rock block wall.

A. Description of Walls.

The walls were constructed of granite blocks, each nominally 2' x 2' x 4', procured from West Chemsford, Mass. The compressive strength of the granite was 29000 psi. The mortar mix was 1 part cement to 3 parts sand. The walls had the following exterior dimensions:

Height, ft.	Width, ft.	Thickness, ft.
10	30	4
10	30	6
20	100	10

B. Results of Tests.

The results of each round of firing are given in Firing Record No. P38298. The average results are summarized in Table IX, in this report. Due to reasons already mentioned, the observed penetrations and craters were not representative of those which would occur in massive monolithic granite. The performance and functioning of the various types of projectiles is summarized in the following paragraphs.

The 76 mm H.E. shell M 42, inert loaded, concrete piercing M 78 fuze, were invariably ruptured on impact with the granite wall even at striking velocities as low as 1170 ft/sec. When the M 42 shell was H.E. loaded, C.P. M 78 fuzes, over 50% low orders resulted, indicating that the shell were collapsing before fuze functioning took place. Apparently the H.E. type of shell with C.P. fuzes is too weak to resist satisfactorily impact on rock.

The 155 mm T27E1 shell was not deformed or ruptured at striking velocities as high as 2750 ft/sec. This shell is an experimental type which was made from a 155 mm M112 A.P. by reaming out and lengthening the explosive cavity, giving a wall thickness of 1.22 inches, and an explosive capacity of about 5%. Apparently, the T27E1 is a type that is about what is needed to resist deformation on impact against hard rock.

The A.P. types of projectiles were not deformed on striking the granite walls. The tungsten carbide cores of the HVAP projectiles were shattered.

C. Structural Behavior of Granite Block Walls.

When an individual block was struck by a projectile, the fracture surfaces emanating radially from the point of impact did not extend across the mortar into the adjacent blocks. Instead, fracture proceeded from the first block along the mortar bond, extending over large areas. The result was that large volumes of blocks were loosened and subsequently tumbled out on to the ground. In view of this result, a wall such as those fired on would be less resistant than an equal volume of rock in the monolithic state.

In order to improve the resistance of rock block walls to projectile impact, the following principles of design are recommended.

a. It is important to use high strength bonding material, one that is more or less comparable in strength to rock. The purpose is to cause the fracture cracks which emanate from the point of impact to extend transversely across the bonding material into the adjacent blocks, thus making the wall similar to a monolithic structure in resistance to projectile impact.

b. The size of the rock blocks should be as large as is practicable. The object is to make the dimensions of the block large relative to the projectile in order to minimize edge-effect.

TABLE IX

RESULTS OF FIRING ON GRANITE BLOCK WALLS

Projectile	No. Rds. in Ave.	Ave. Strik. Vel., ft/sec	Wall thick ft.	Ave. Dimensions of Crater, In. Depth	Dia	Condition of Projectile
37 mm A.P.M74	3	1130	4	2.8	14	Intact
	3	1880	"	3.8	9	"
	2	2600	"	5.0	15.5	"
76 mm A.P.M79	4	1040	6	8.3	15.9	"
	4	1890	"	15.5	40.5	"
	3	2570	"	22.3	30.7	"
76 mm H.E.M42 Inert loaded;C.P. M78 Fuze	3	1170	10	3.0	14.3	Ruptured
	3	1540	"	3.3	21.4	"
	3	2010	"	7.2	26.7	"
76 mm H.E.M42 live loaded; live CPM78 fuze	3	1160	10	2.8	19	{3 High order,
	3	1530	"	4.2	23.6	5 low order,
	3	2040	"	7.8	26	1 Dud.}
76mm H.E. A.P.C. M62	3	1480	10	5.8	25	High order
	3	2010	"	8.8	35.5	" "
	3	2540	"	13	42	" "
90 mm A.P. M77	3	790	10	6.7	18	Intact
	3	1680	"	13	30.5	"
	3	2680	"	29	Lost.	"
155 mm T27E1, H.E. loaded live fuzed	3	1560	10	14	45.2	(2 High order (1 Dud intact
	3	2730	"	42	69.5	(2 High order (1 Dud intact
155 mm T27E1, H.E. loaded, inert fuze.	3	1560	10	17.5	48.5	Intact
	1	2740	"	38	61	"
90 mm T30 E16 HVAP	3	3290	10	29	*	Cores broken

*The typical crater of HVAP was a wide shallow cone 8" deep x 35" dia. with a cylindrical hole at the apex 21" deep x 1.7" dia., 29" total depth.

SUMMARY

From the results of the firings the following formula for penetration of single rounds was deduced.

$$P = k_p (W/d^2) d^{1/6} (V/1000)$$

where P = Penetration, inches.

W = Weight of Projectile, lbs.

d = Projectile diameter, inches.

V = Striking velocity, ft/sec.

k_p = 2.7 for hard rock

k_p = 4.7 for soft rock

The crater volume excavated by single rounds is given by the formula $S^{1/3} = k_s (W/d^2) d^{1/6} \left(\frac{V}{1000}\right)$
where, W, d, and V are in units given above,

S = crater volume, cubic inches

k_s = 3.9 for hard rocks

k_s = 5.8 for soft rocks

The volume excavated by repeated rounds is given by $S_n = S_1 n^{1.3}$
where S_n is the volume after n rounds, S_1 the volume after one round, $n \leq 5$.

The penetration into rock was found to be approximately inversely proportional to the cube root of the compressive strength. The relation between compressive strength and penetration is modified by the degree of weathering and fissuring in the natural rock.

Granite block walls such as those fired on were found to be inferior to massive granite due to extensive cracking along the mortar bond. For improving the resistance of rock block walls to projectile impact, it was recommended that high strength bonding material be used, and that the size of the blocks be as large as is practicable.

Standard H. E. artillery shell with concrete piercing fuzes were ruptured on striking granite whereas an experimental semi-armor piercing projectile containing about 5% explosive was not deformed on granite.

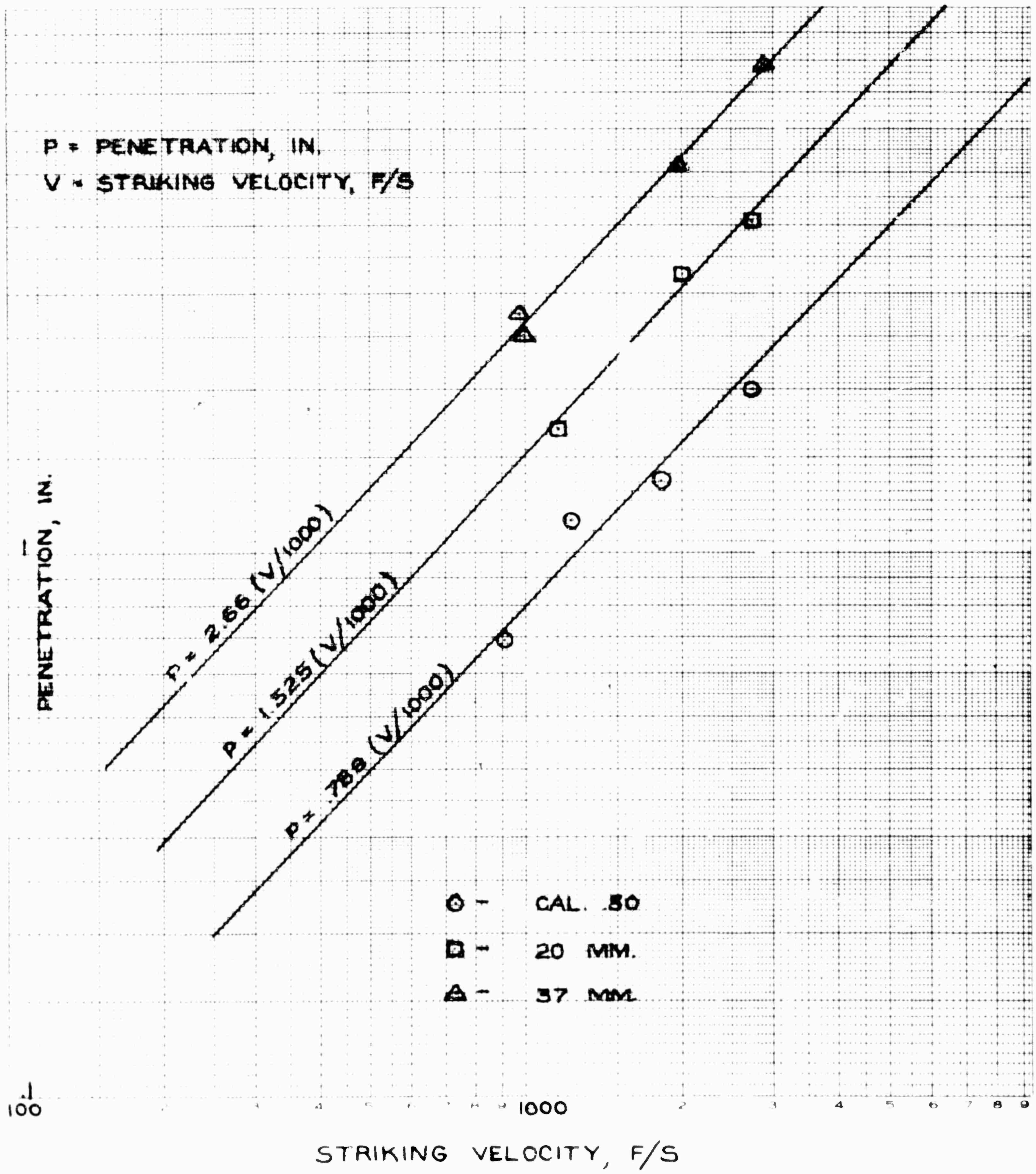
N. A. Tolch

N. A. Tolch

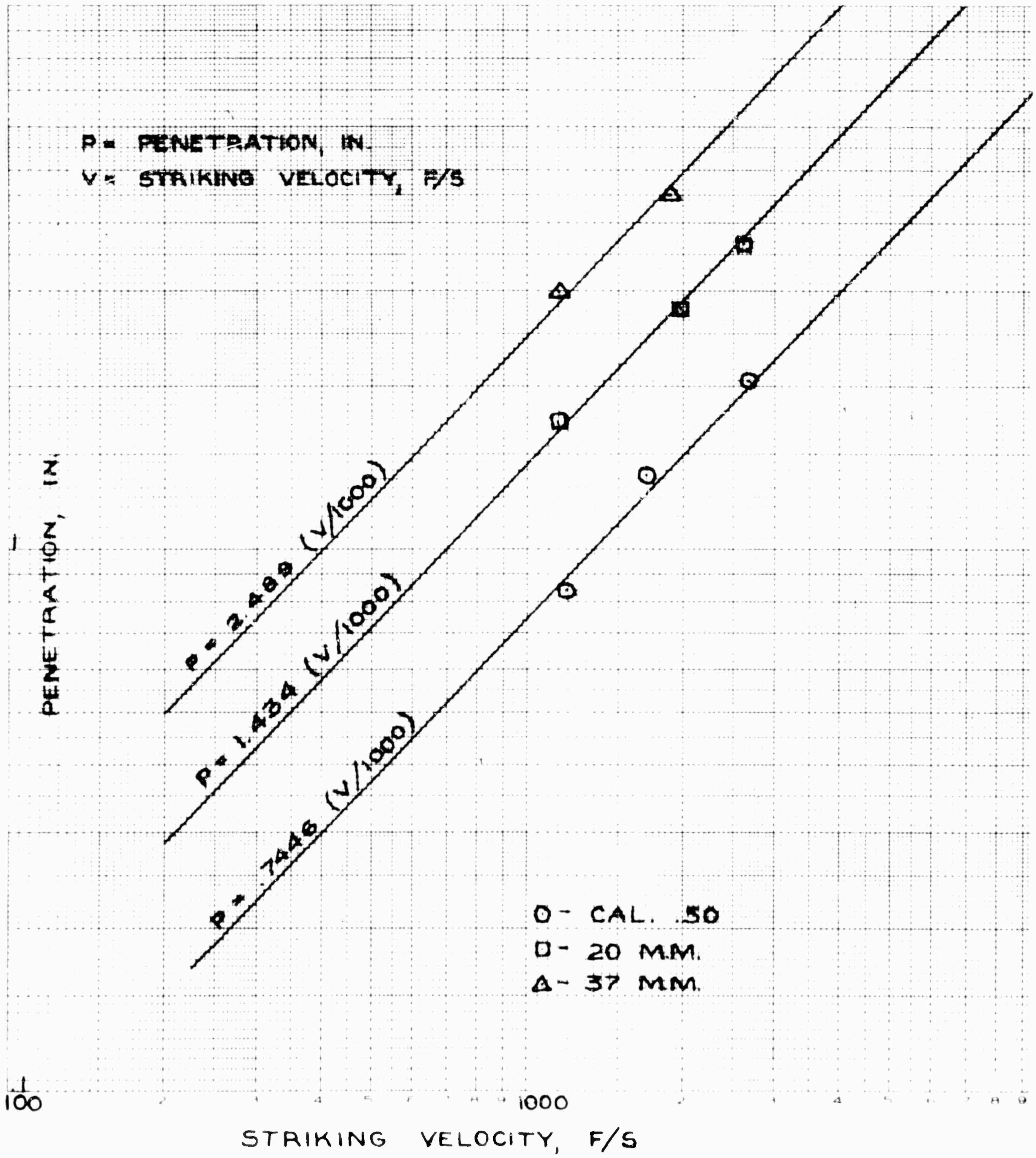
A. V. Bushkovitch

A. V. Bushkovitch

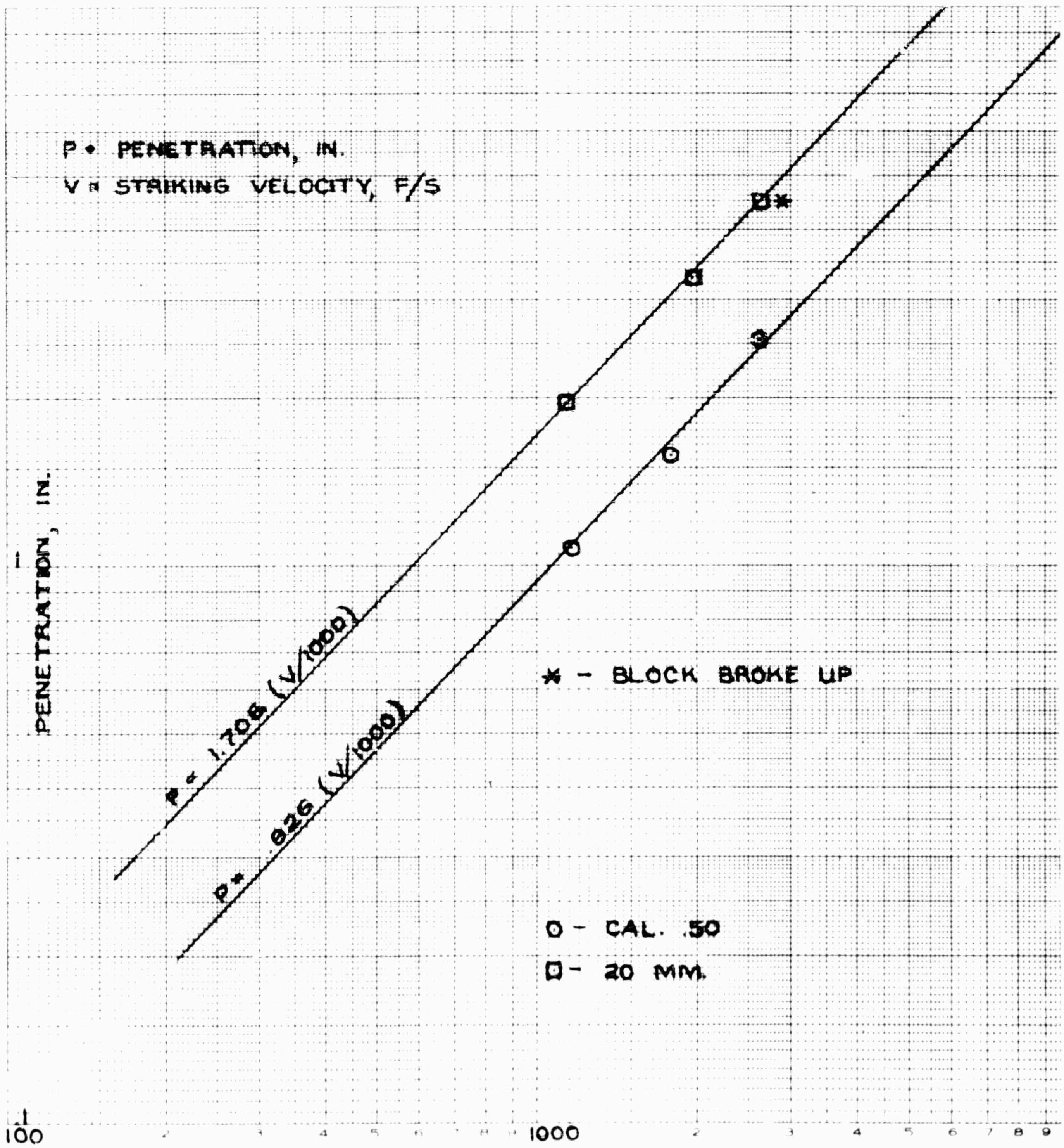
PLOT I. PENETRATION OF VARIOUS PROJECTILES INTO GRANITE vs STRIKING VELOCITY (SINGLE ROUNDS)



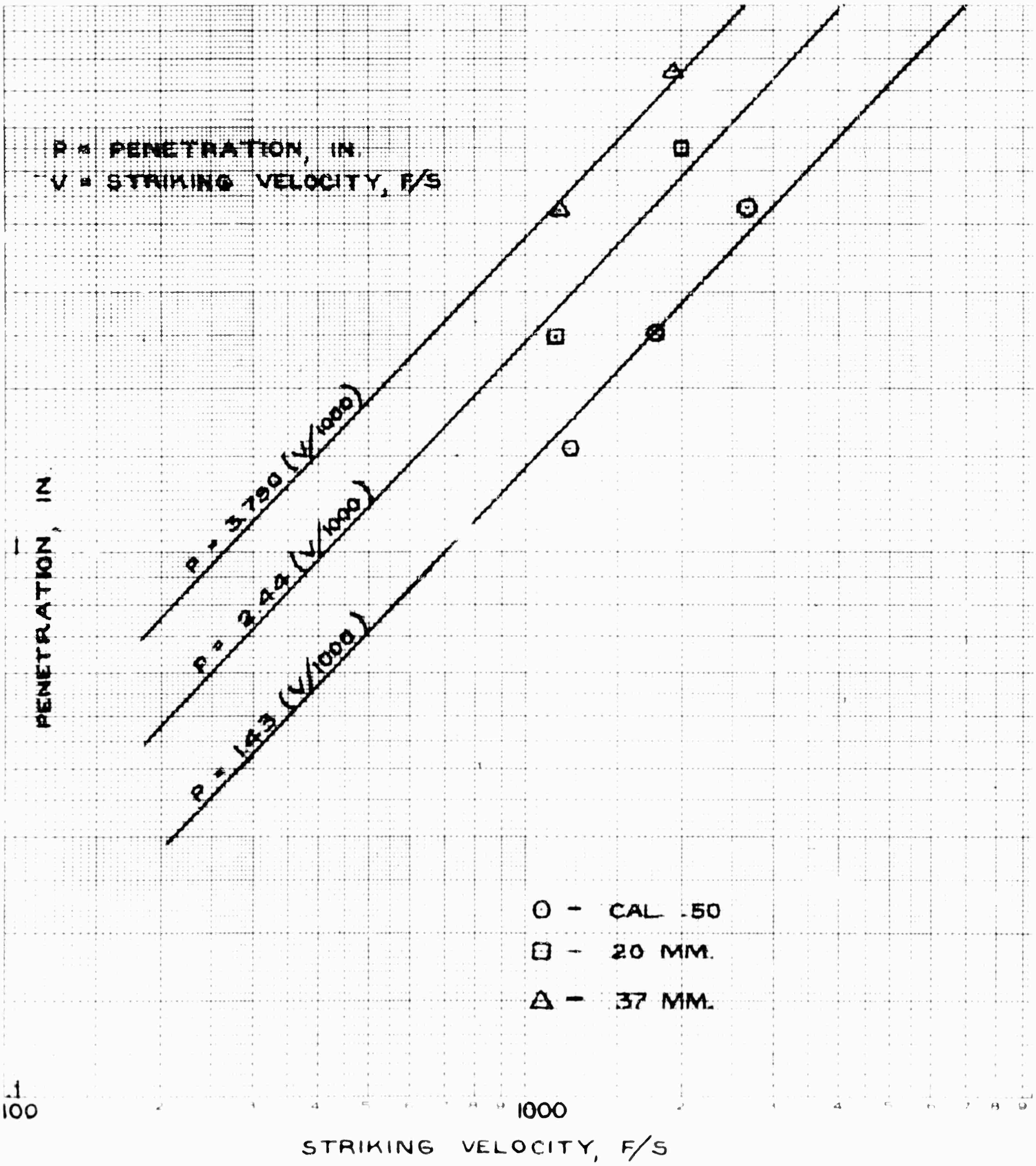
PLOT 2. PENETRATION OF VARIOUS PROJECTILES INTO DIABASE vs. STRIKING VELOCITY (SINGLE ROUNDS.)



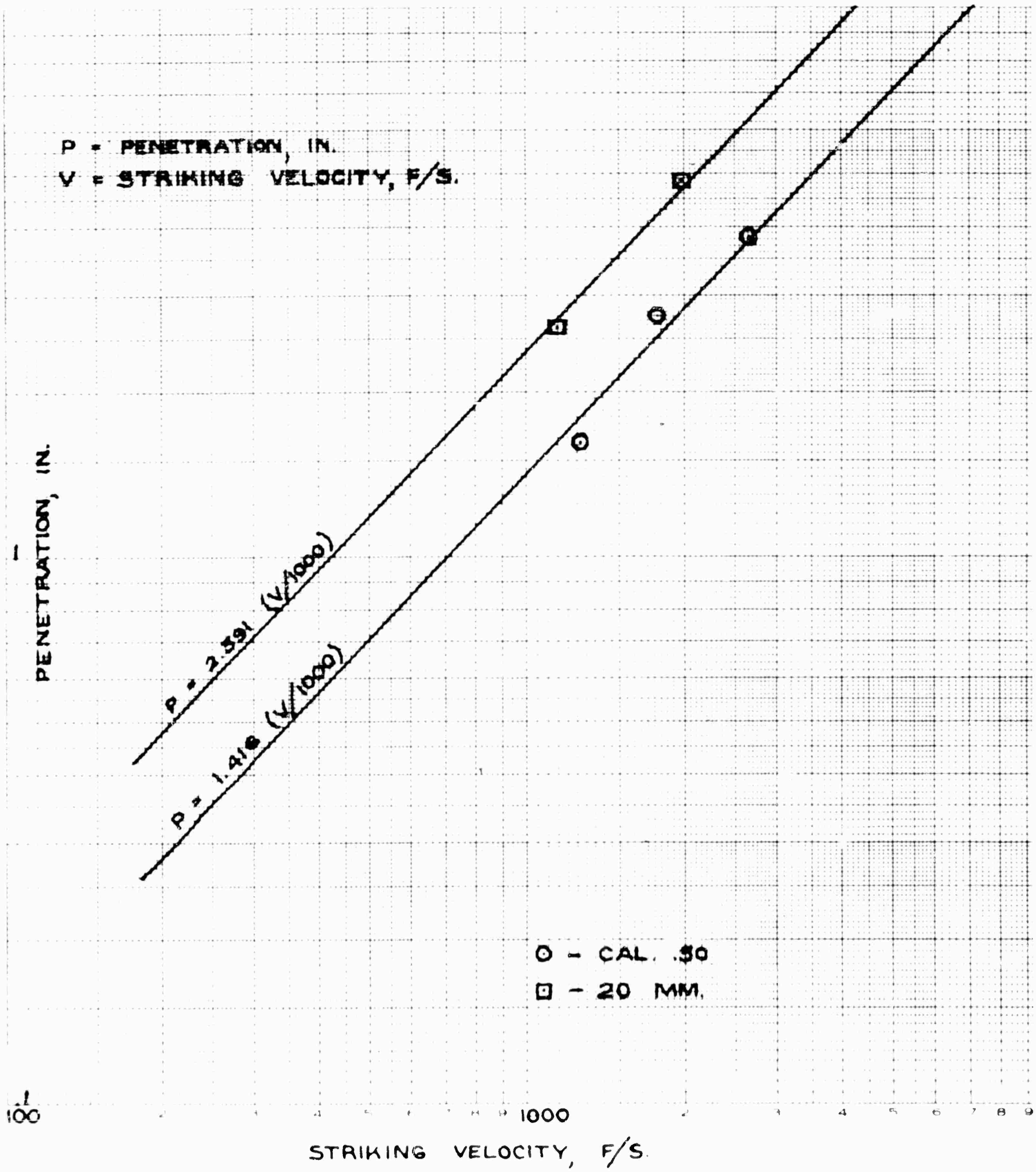
PLOT 3. PENETRATION OF VARIOUS PROJECTILES INTO QUARTZITE vs STRIKING VELOCITY (SINGLE ROUNDS)



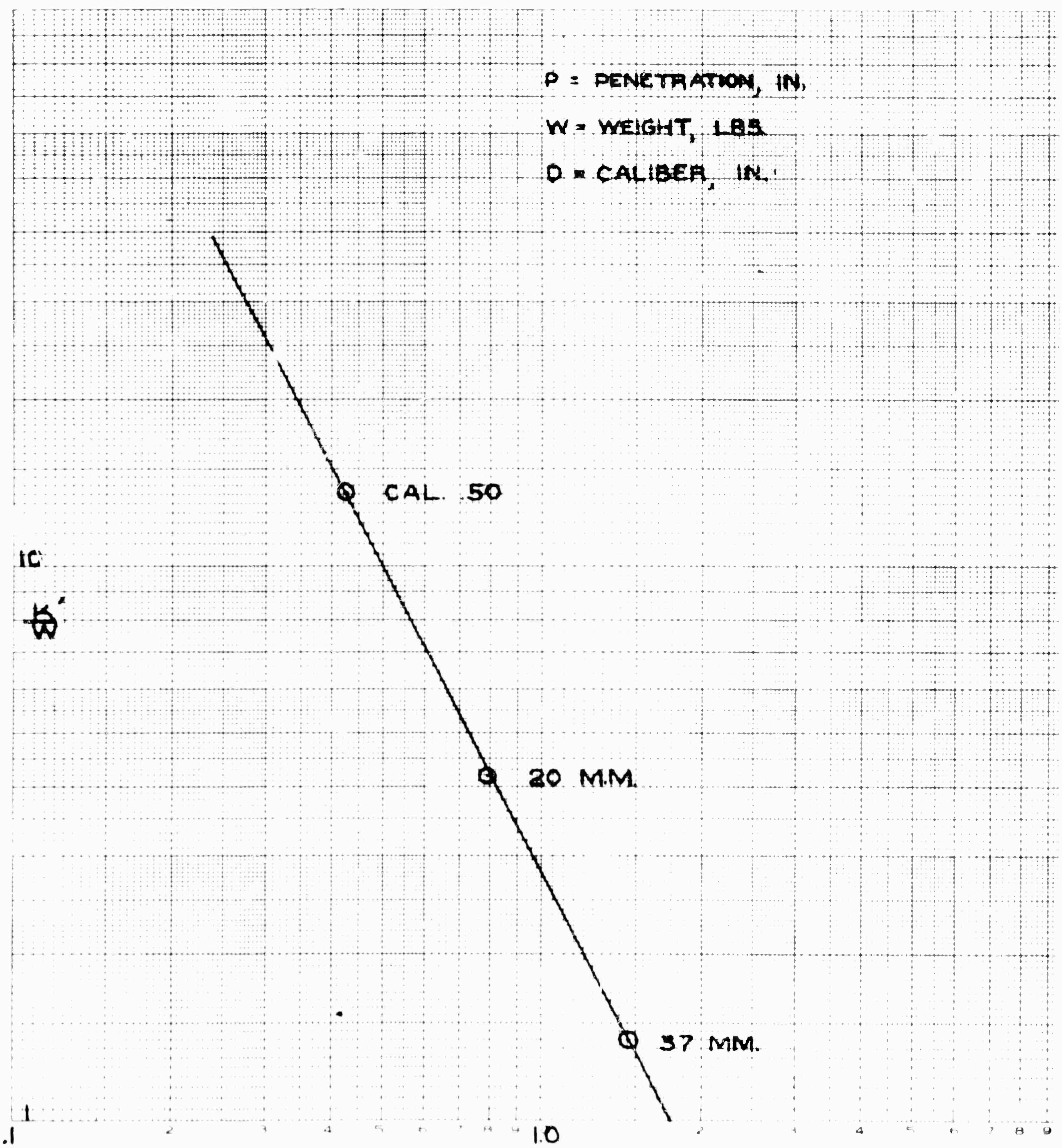
PLOT 4. PENETRATION OF VARIOUS PROJECTILES INTO INDIANA LIMESTONE vs. STRIKING VELOCITY (SINGLE ROUNDS)



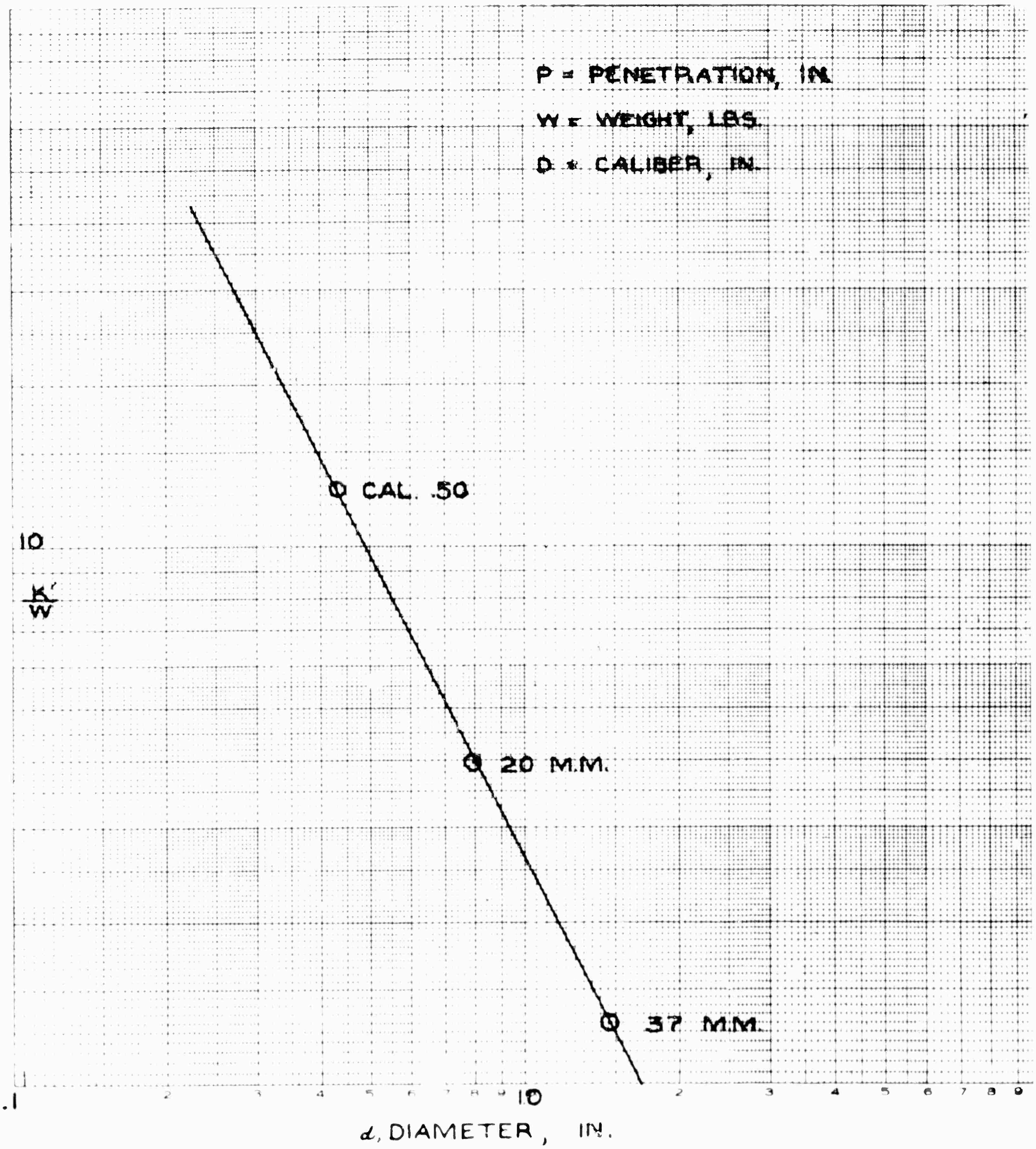
PLOT 5 PENETRATION OF VARIOUS PROJECTILES INTO SANDSTONE vs STRIKING VELOCITY (SINGLE ROUNDS).



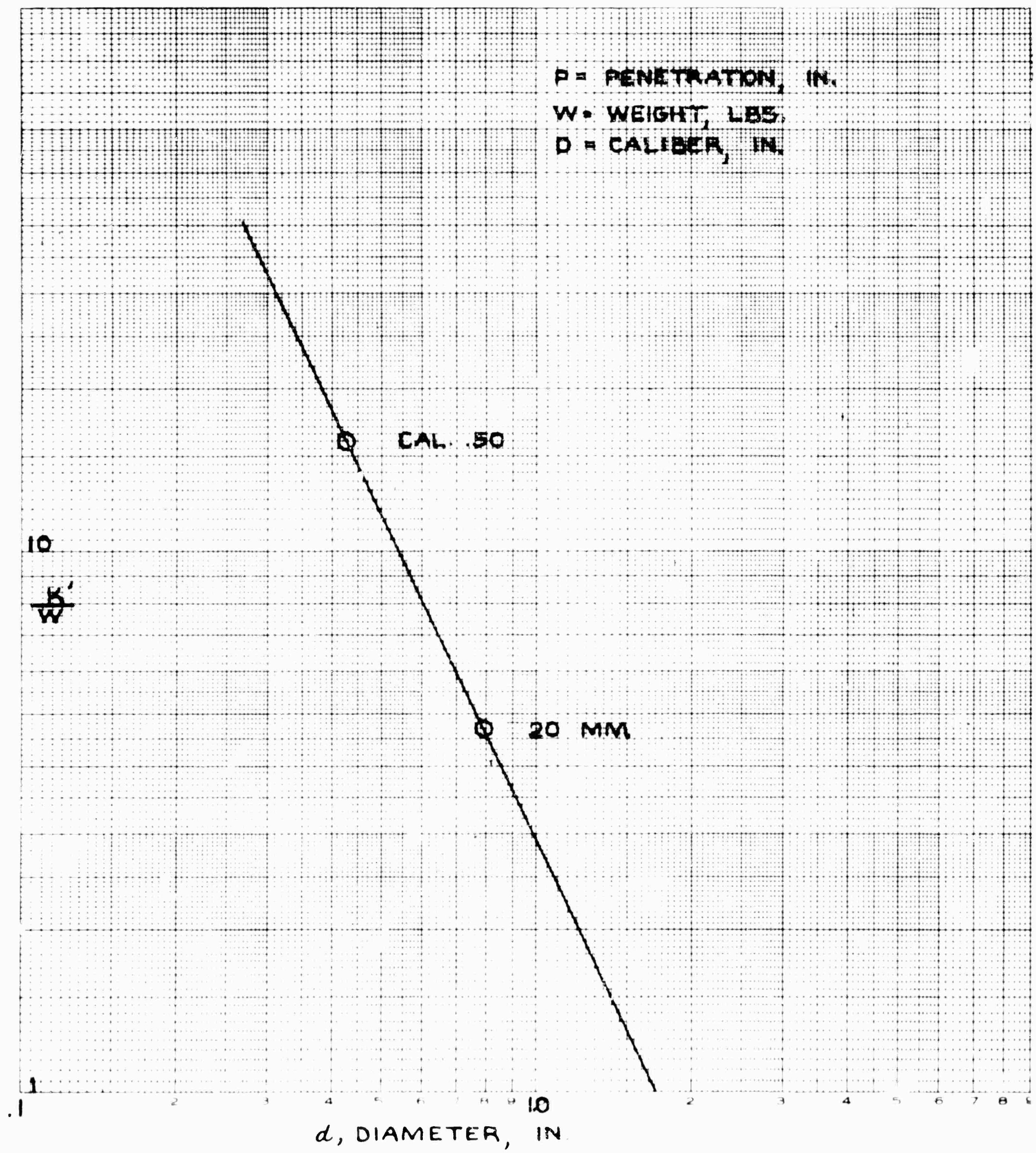
PLOT 6 - K′/W VS d FOR GRANITE.



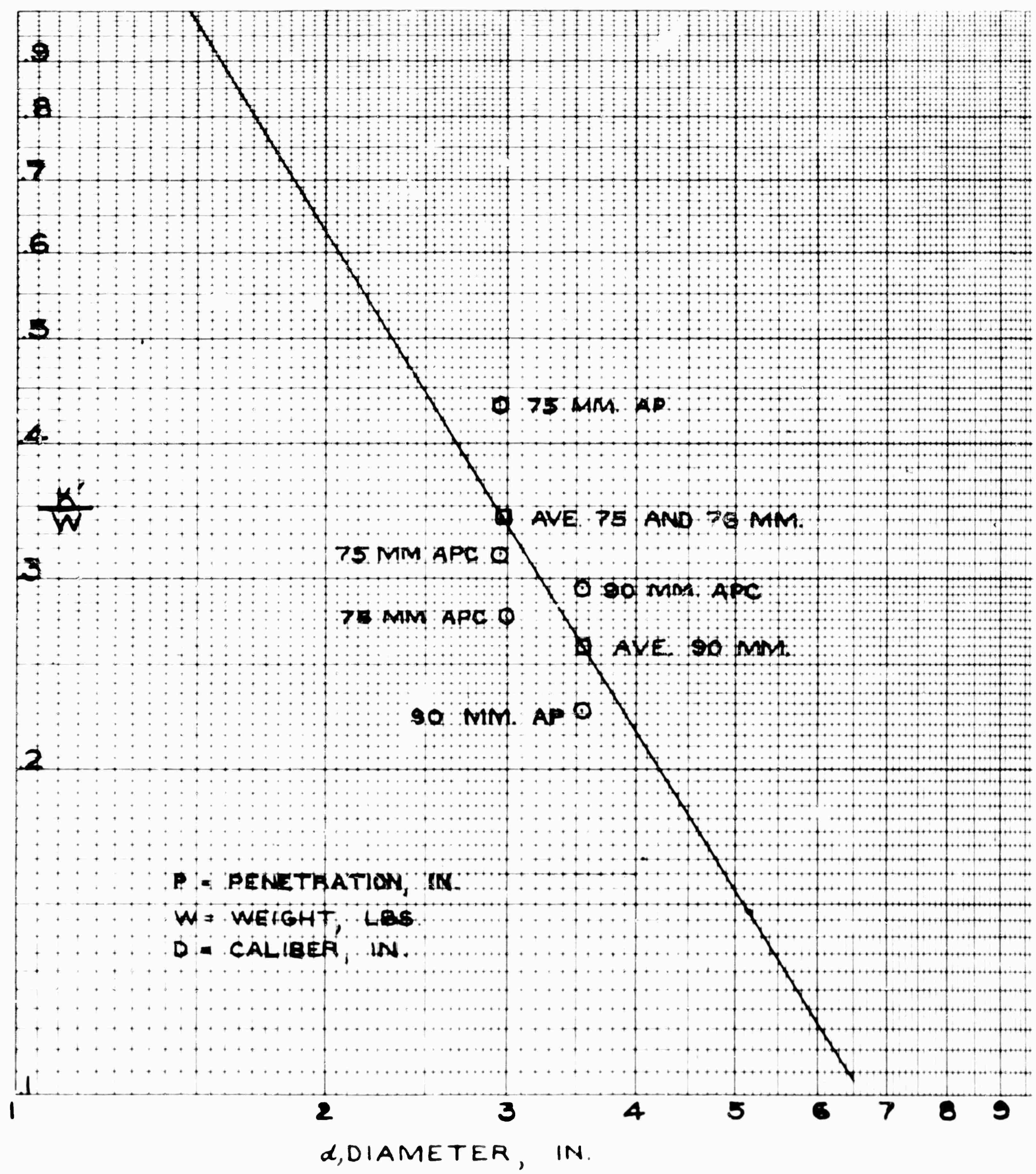
PLOT 7 - K'/W VS d FOR DIABASE.



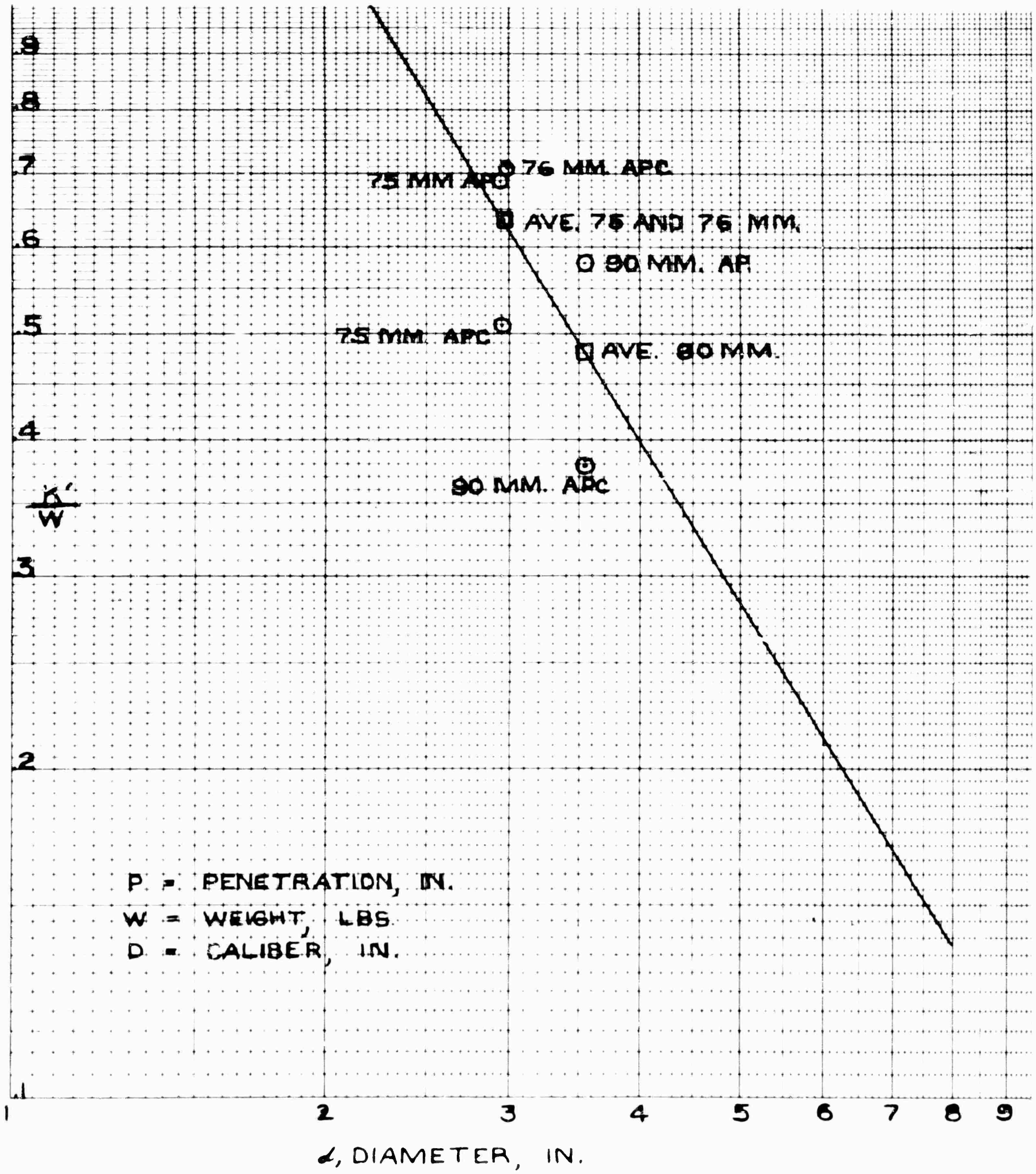
PLOT 8 - K'/W VS d FOR QUARTZITE.



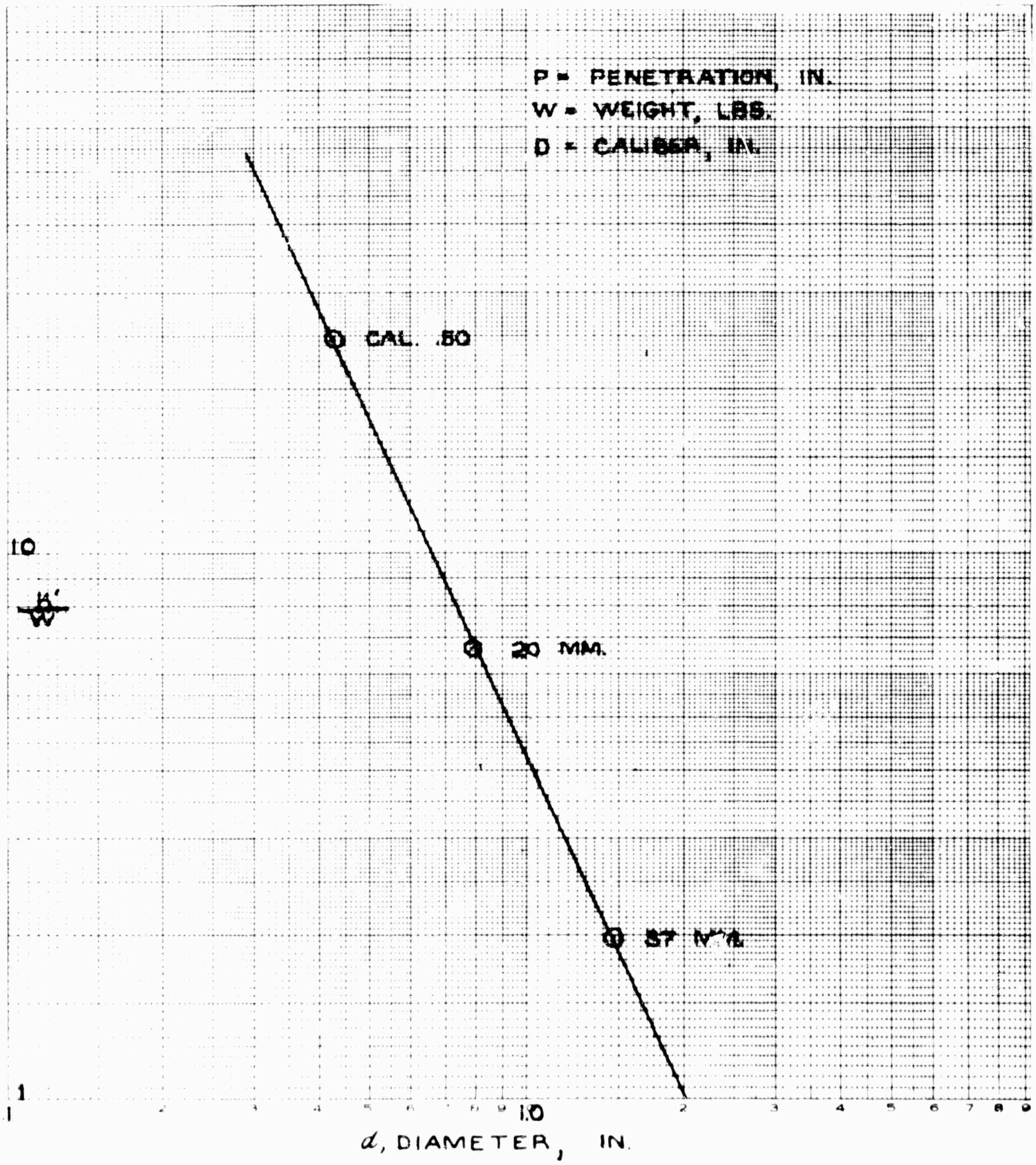
PLOT 9 - K'/W VS d FOR WARSAW LIMESTONE.



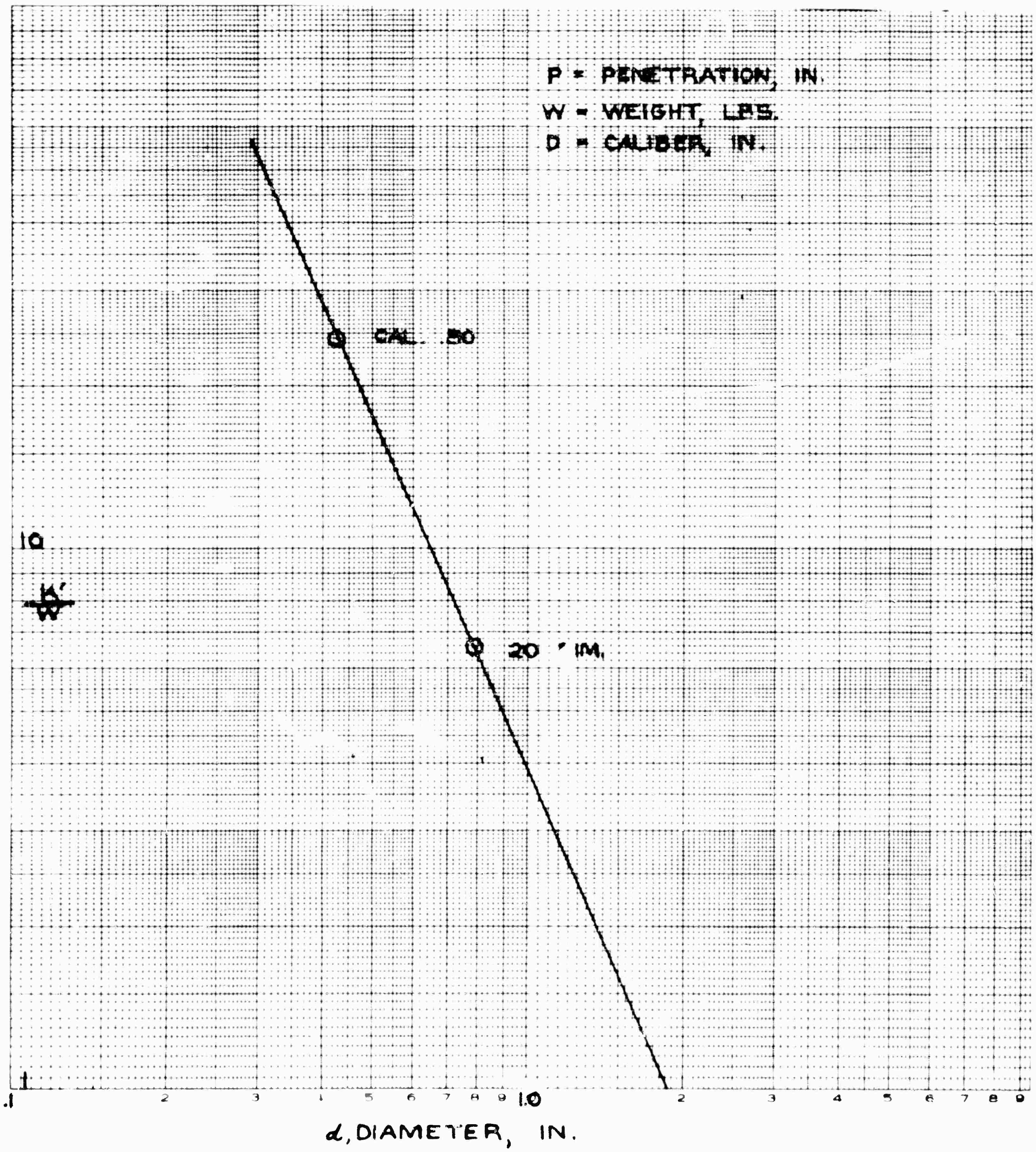
PLOT 10 - K'/W VS d FOR ST. LOUIS LIMESTONE.



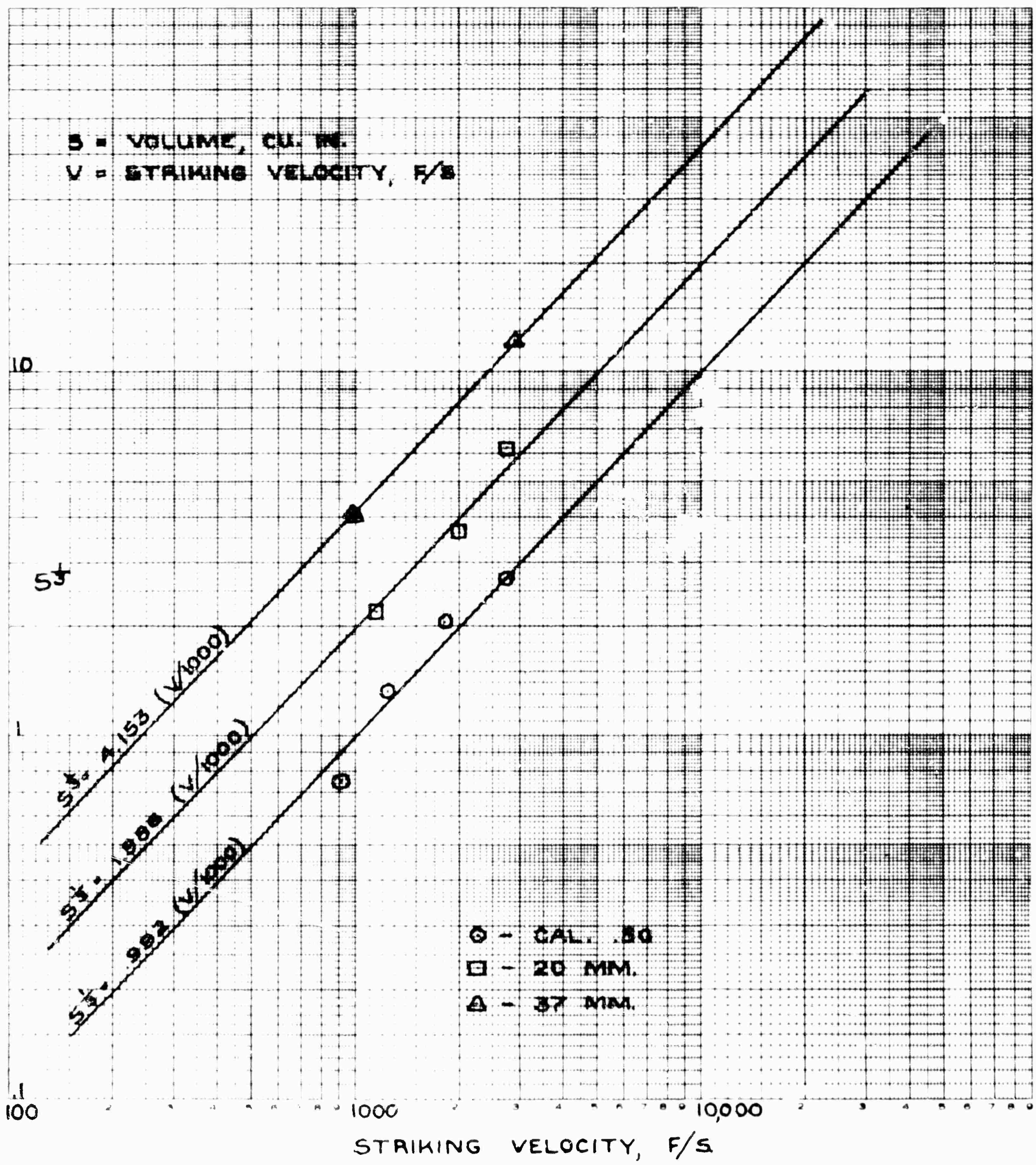
PLOT II - K'/W VS d FOR INDIANA LIMESTONE.



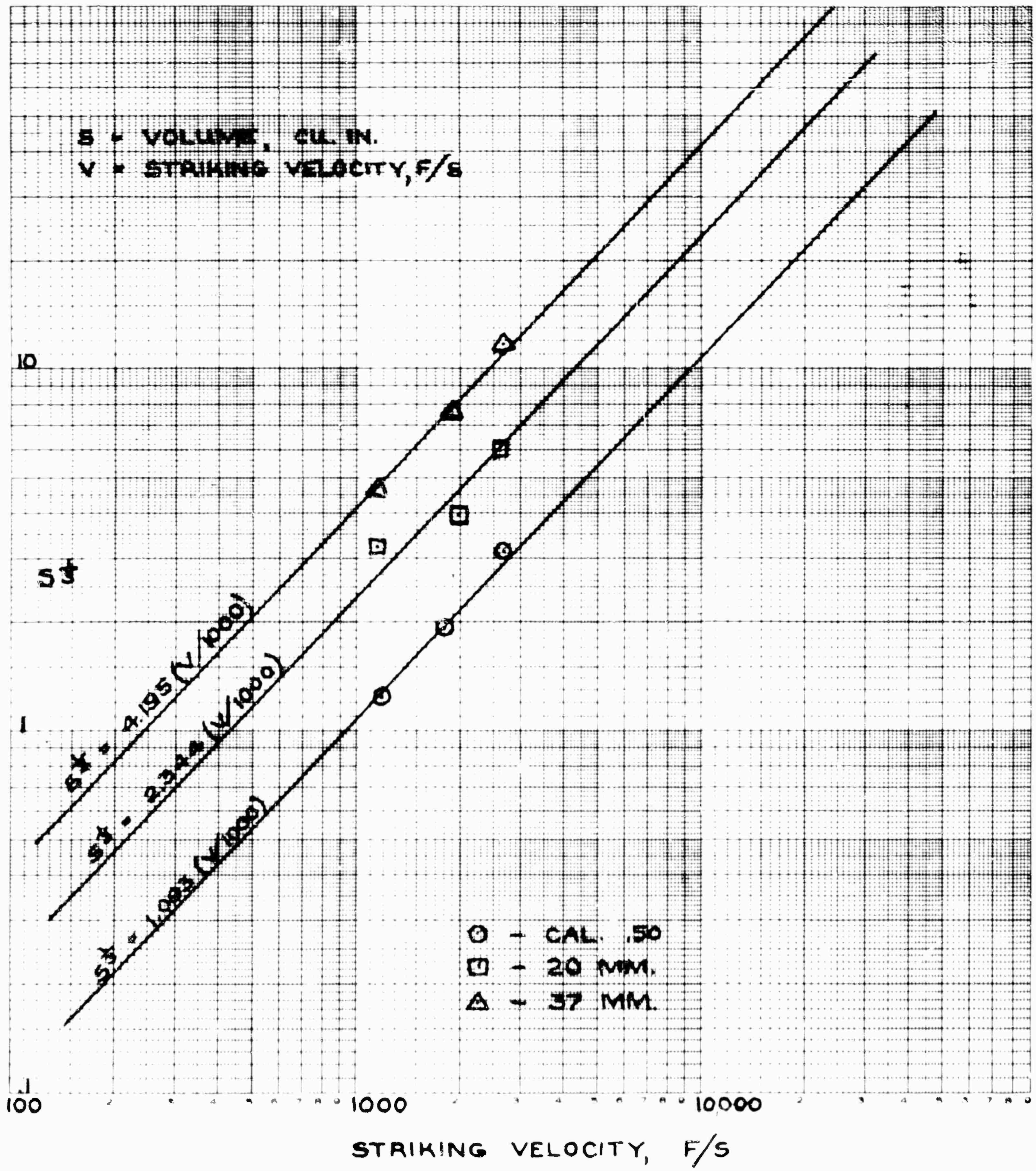
PLOT 12 - K'/W VS d FOR SANDSTONE.



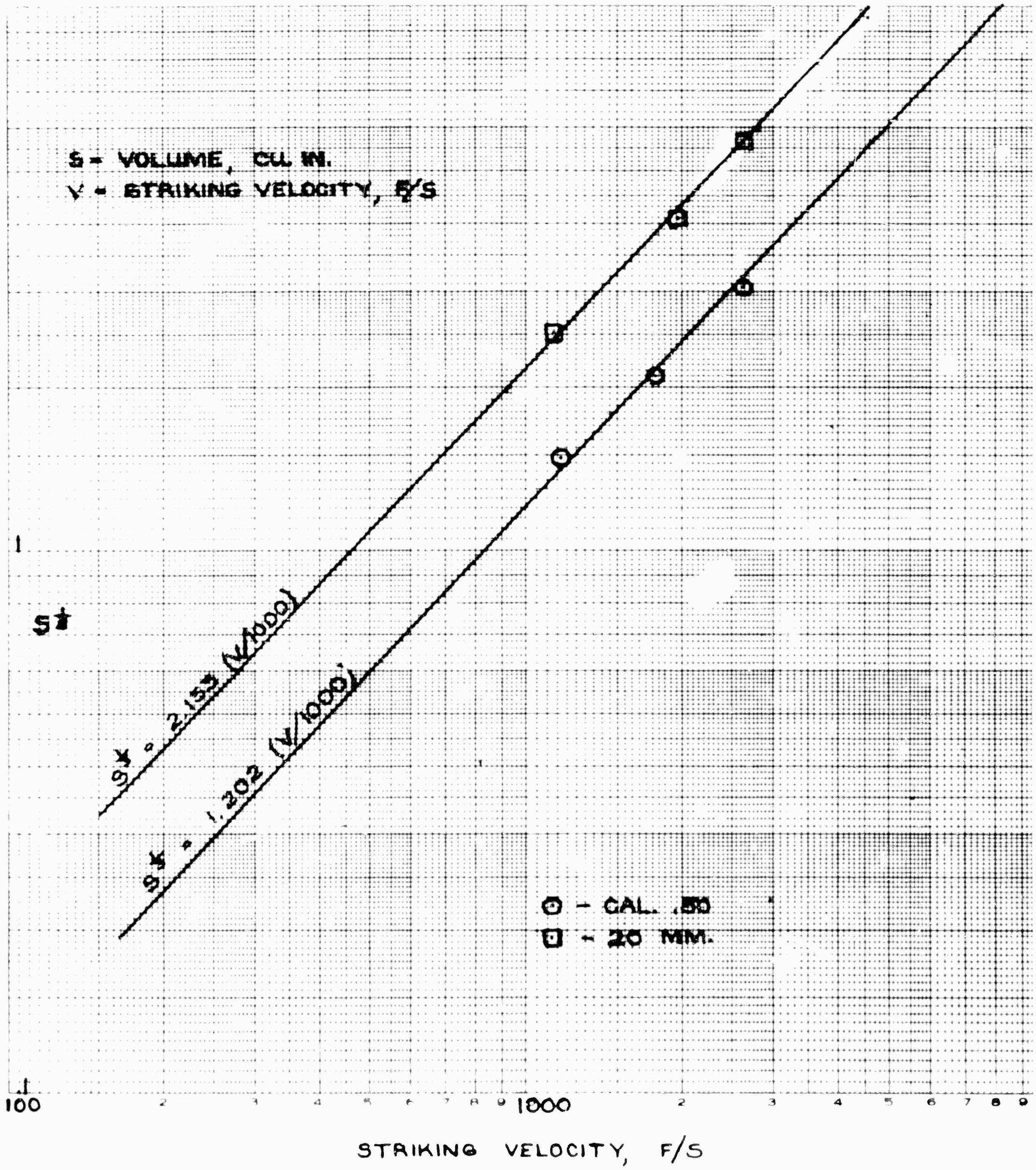
PLOT 13. CUBE ROOTS OF CRATER VOLUMES DUE TO VARIOUS PROJECTILES FIRED INTO GRANITE vs. STRIKING VELOCITY (SINGLE ROUNDS)



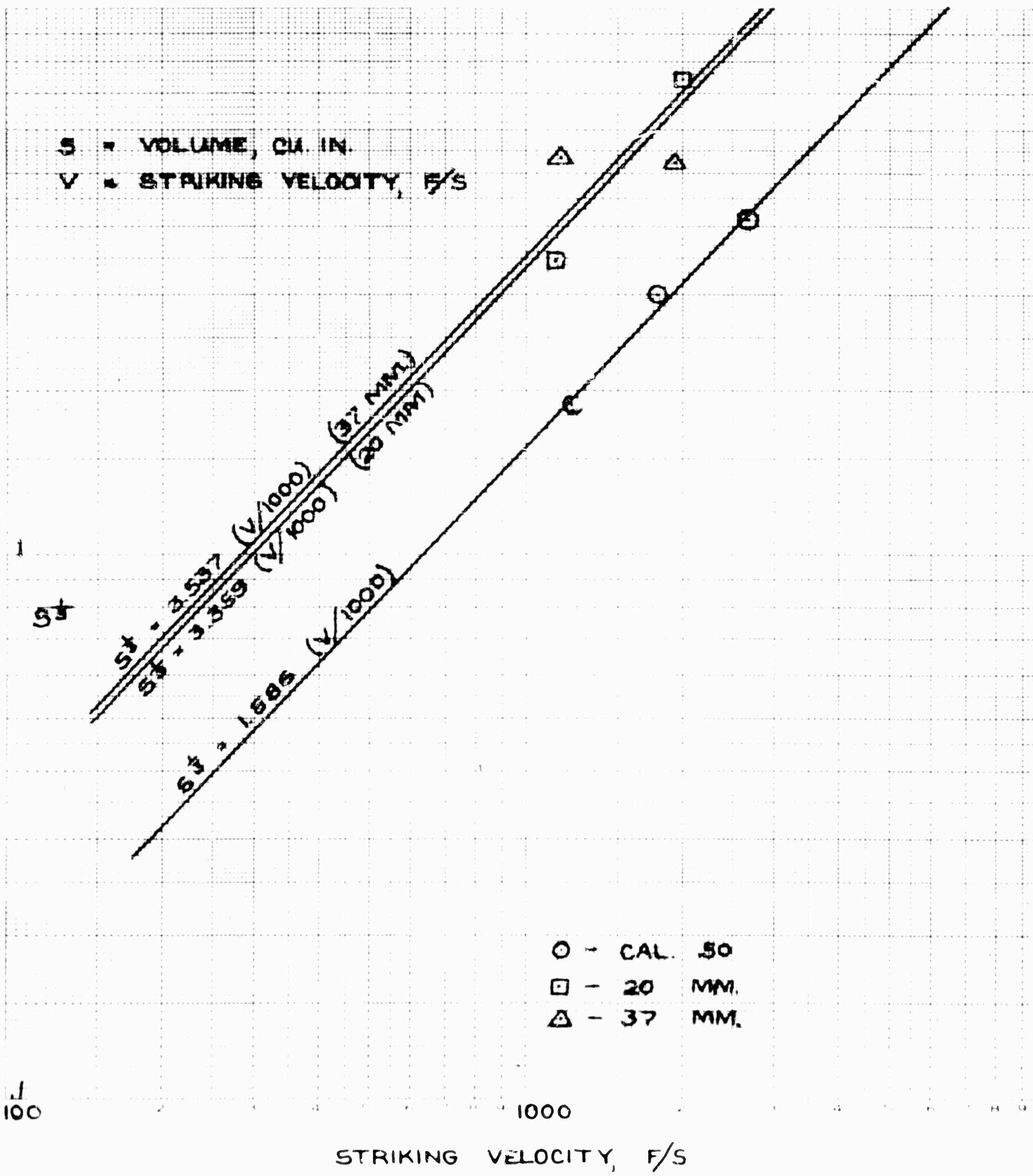
PLOT 14. CUBE ROOTS OF CRATER VOLUMES DUE TO VARIOUS PROJECTILES FIRED INTO DIABASE vs. STRIKING VELOCITY (SINGLE ROUNDS)



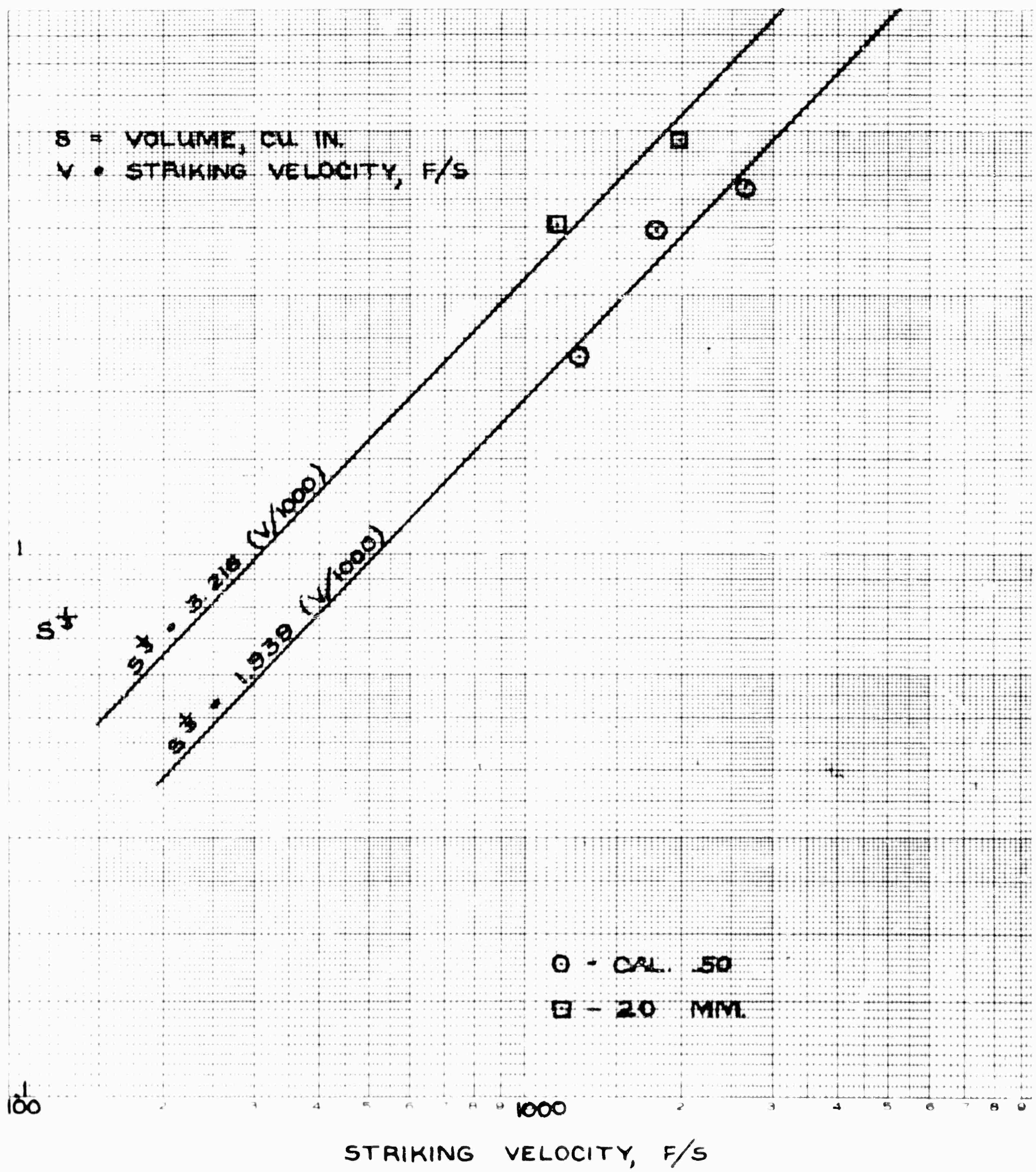
PLOT 15. CUBE ROOTS OF CRATER VOLUMES DUE TO VARIOUS PROJECTILES FIRED INTO QUARTZITE vs. STRIKING VELOCITY (SINGLE ROUNDS)



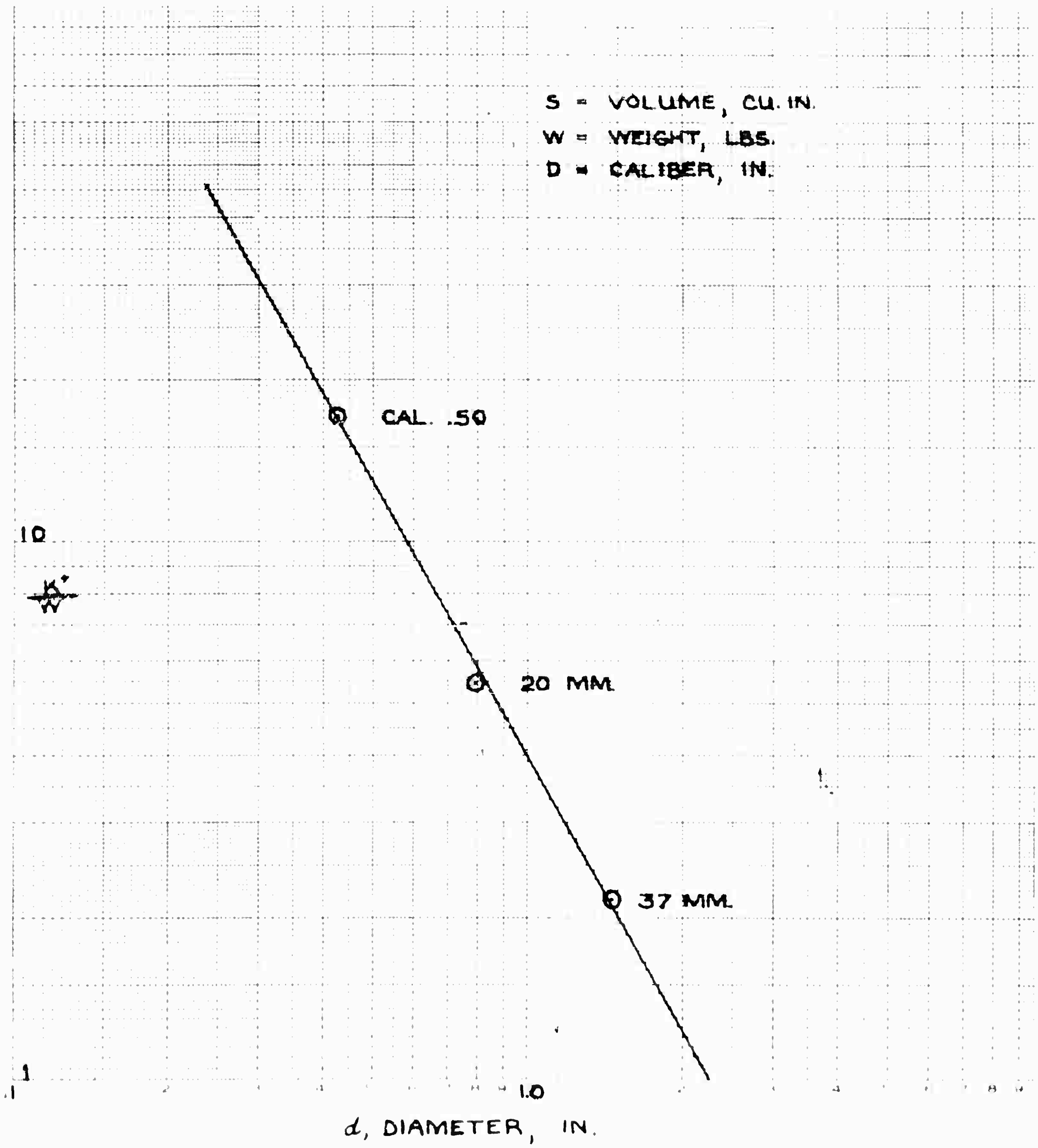
PLOT 16. CUBE ROOTS OF CRATER VOLUMES DUE TO VARIOUS PROJECTILES FIRED INTO INDIANA LIMESTONE vs. STRIKING VELOCITY (SINGLE ROUNDS)



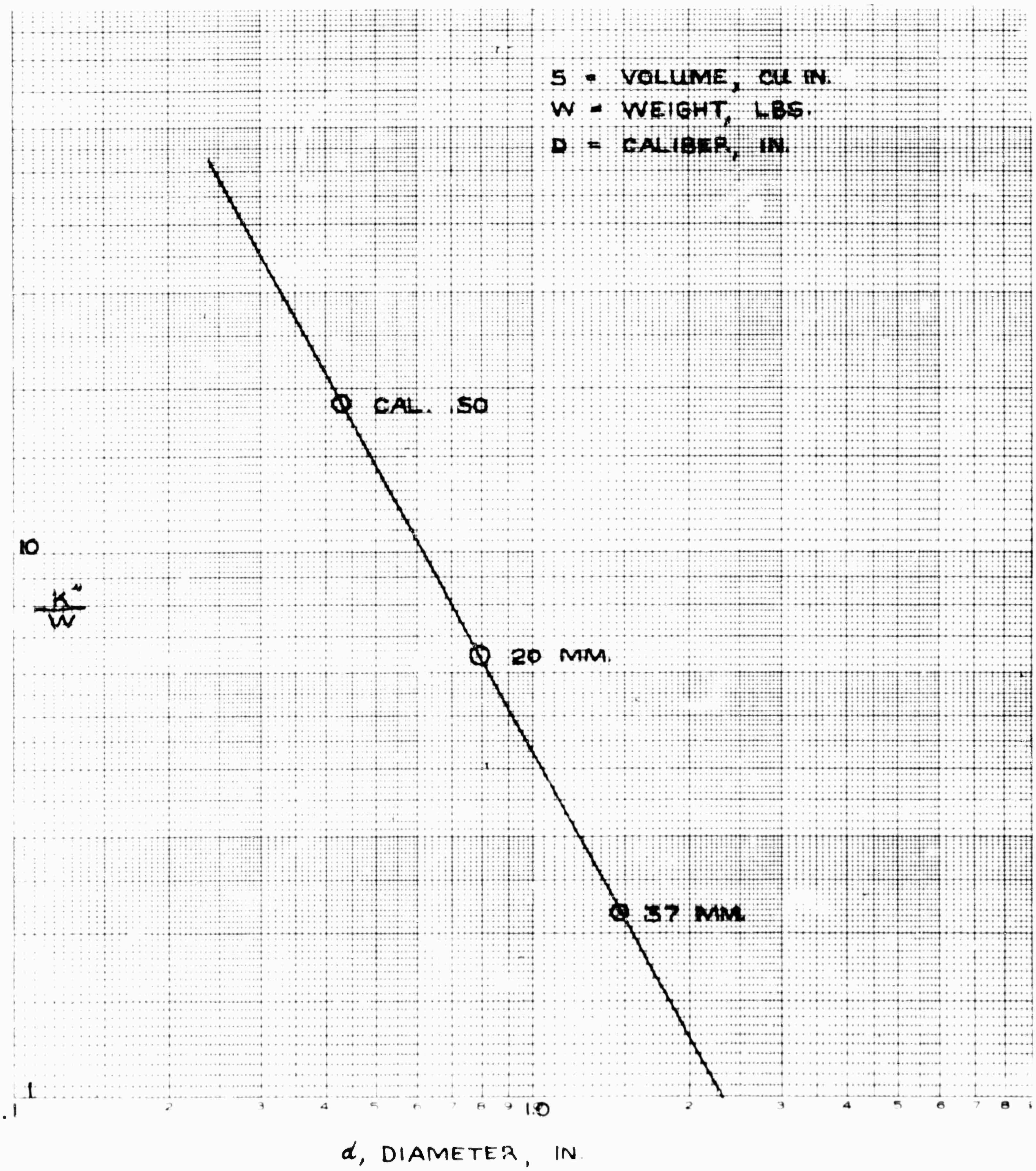
PLOT 17. CUBE ROOTS OF CRATER VOLUMES DUE TO VARIOUS PROJECTILES FIRED INTO SANDSTONE vs. STRIKING VELOCITY. (SINGLE ROUNDS)



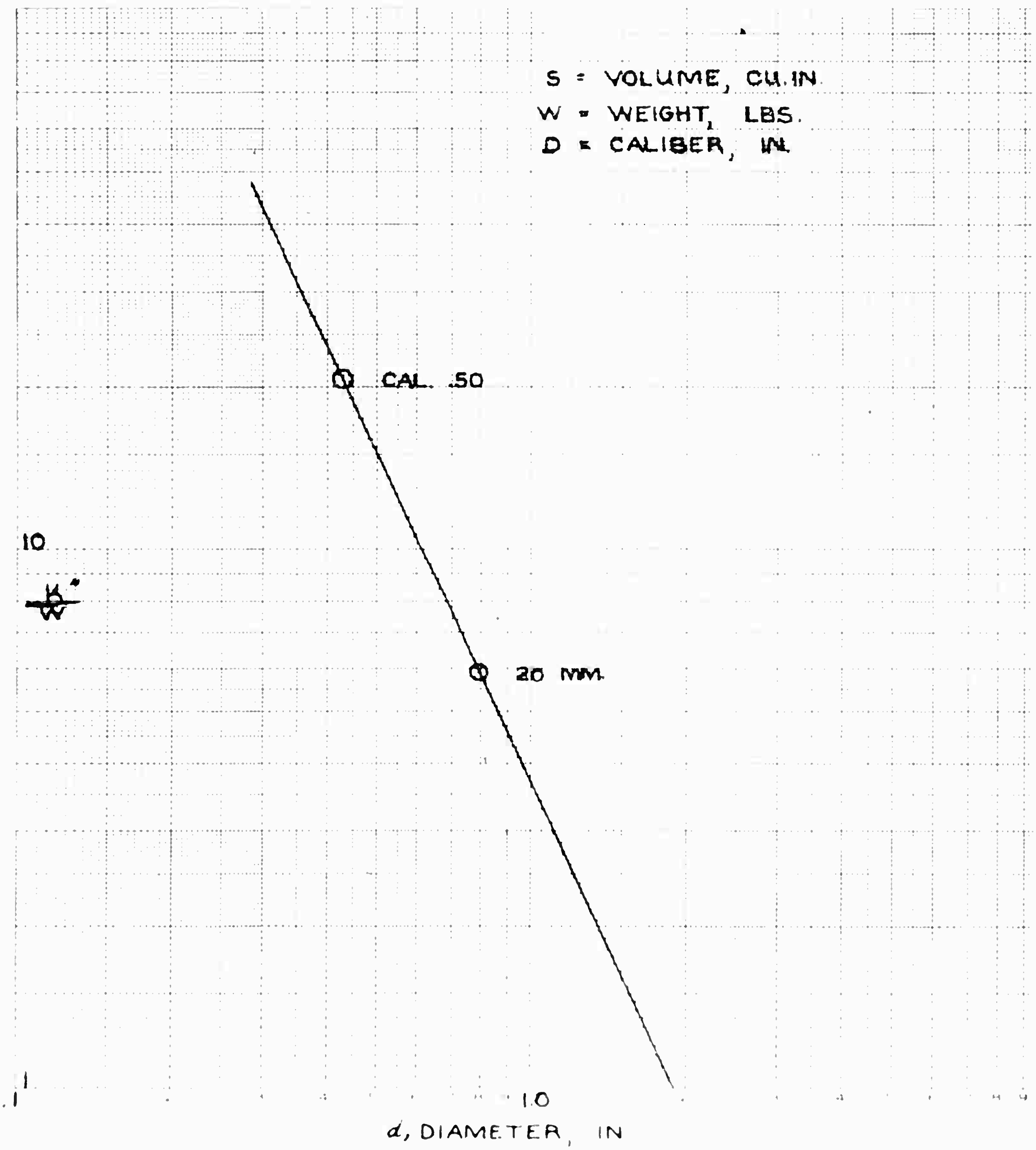
PLOT 18 - K"/W VS d FOR GRANITE.



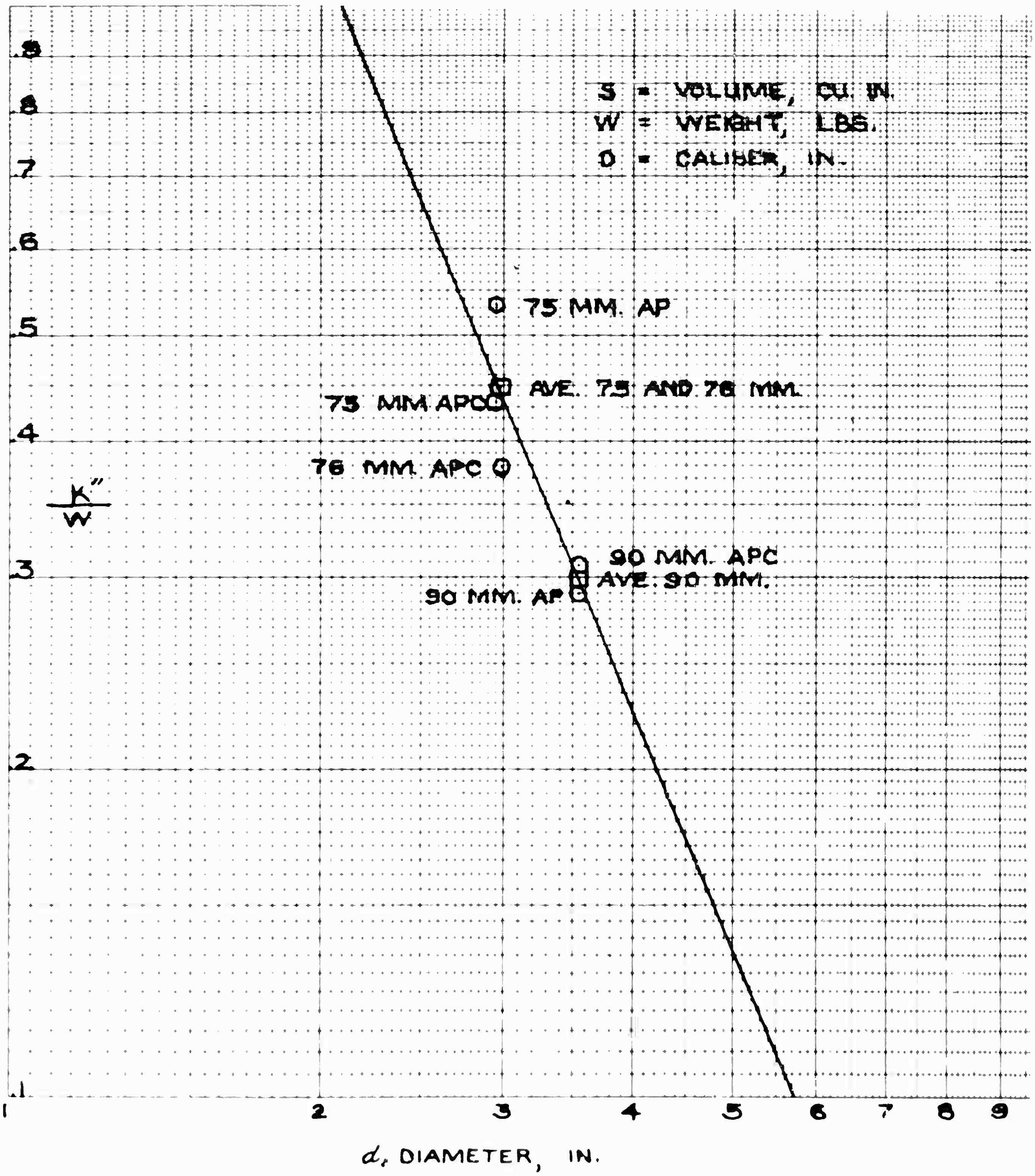
PLOT 19 - K"/W VS d FOR DIABASE.



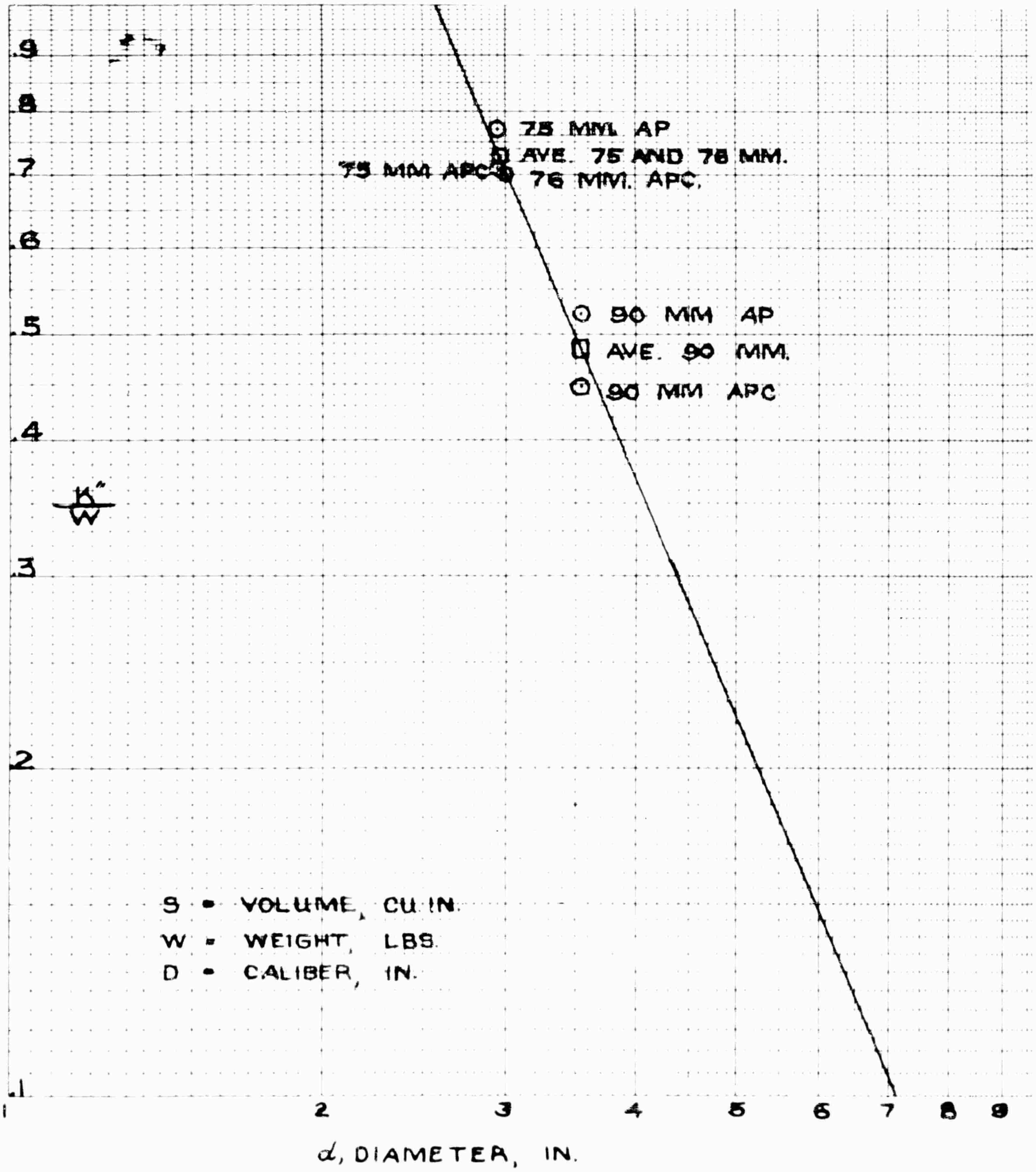
PLOT 20 - K"/W VS d FOR QUARTZITE



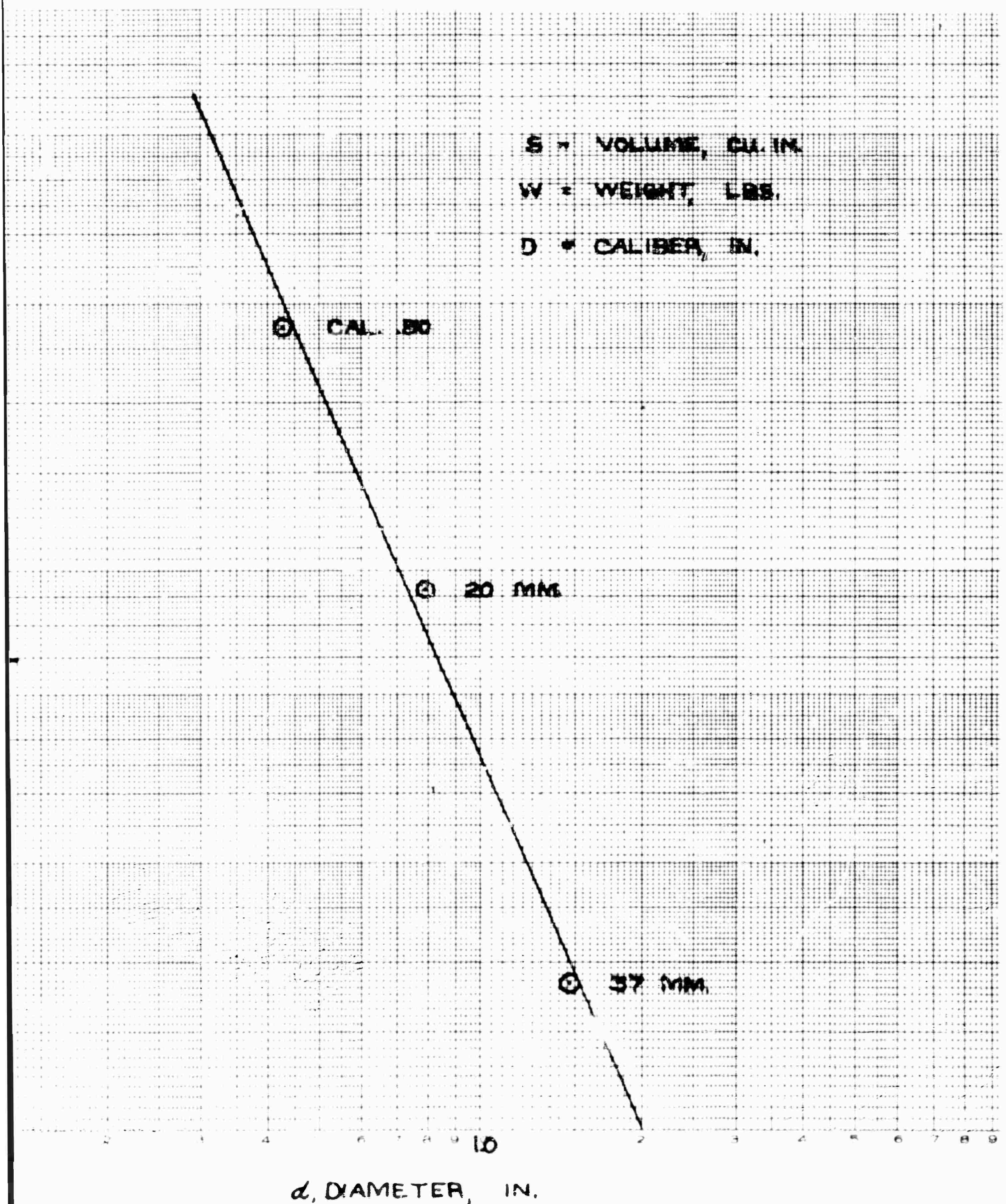
PLOT 21 - K"/W VS d FOR WARSAW LIMESTONE.



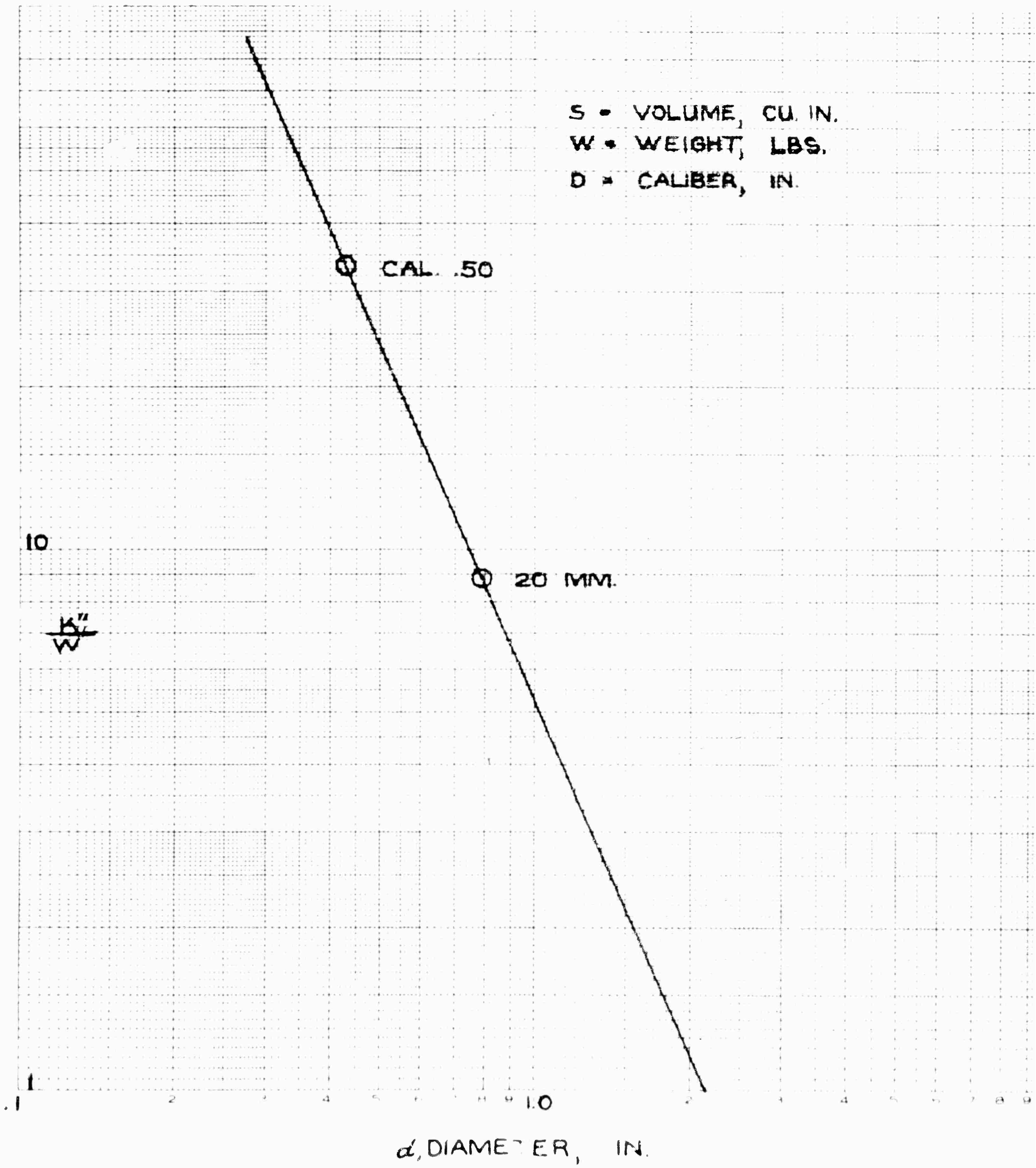
PLOT 22 - K"/W VS d FOR ST. LOUIS LIMESTONE.



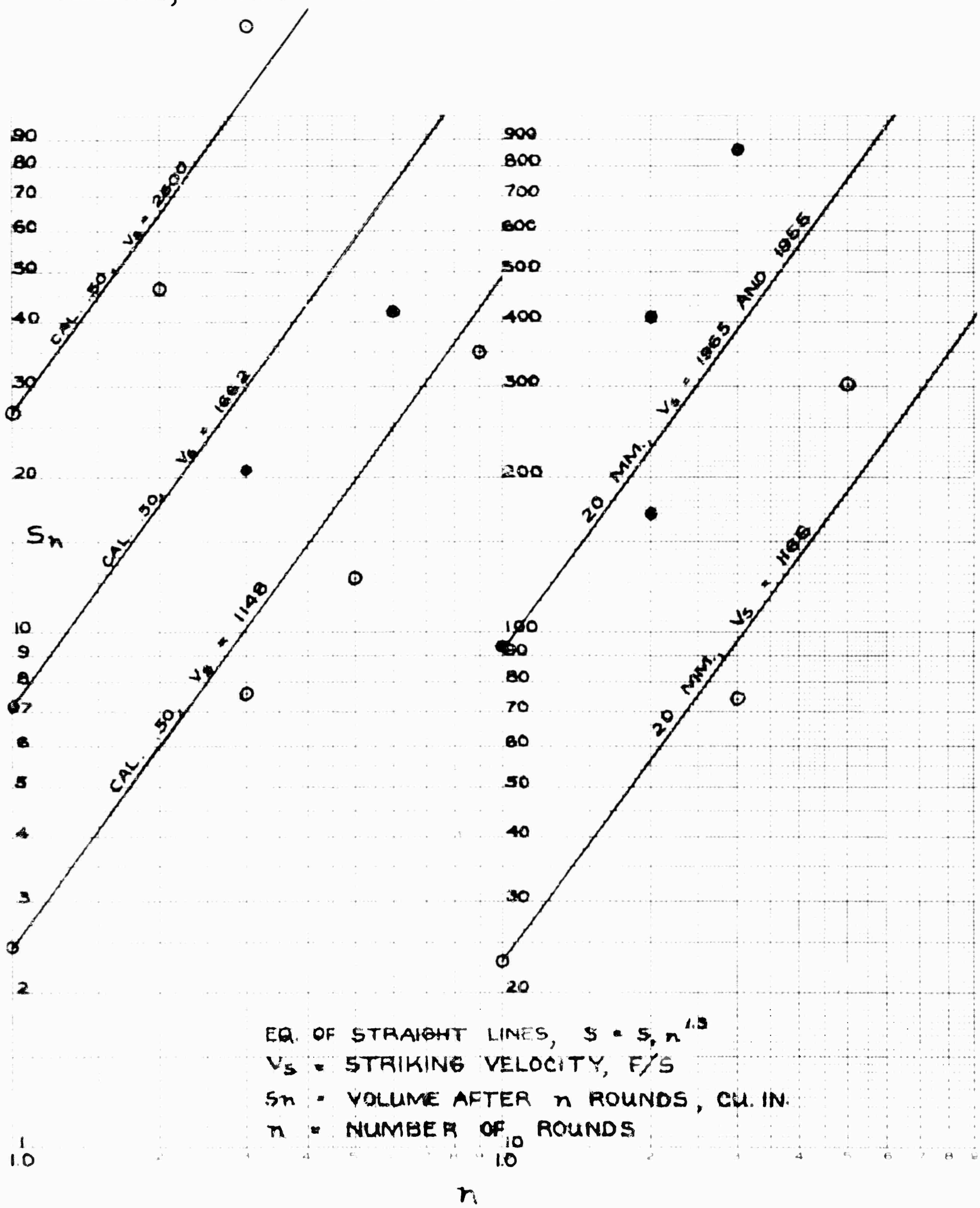
PLOT 23 - K''/W VS d FOR INDIANA LIMESTONE.



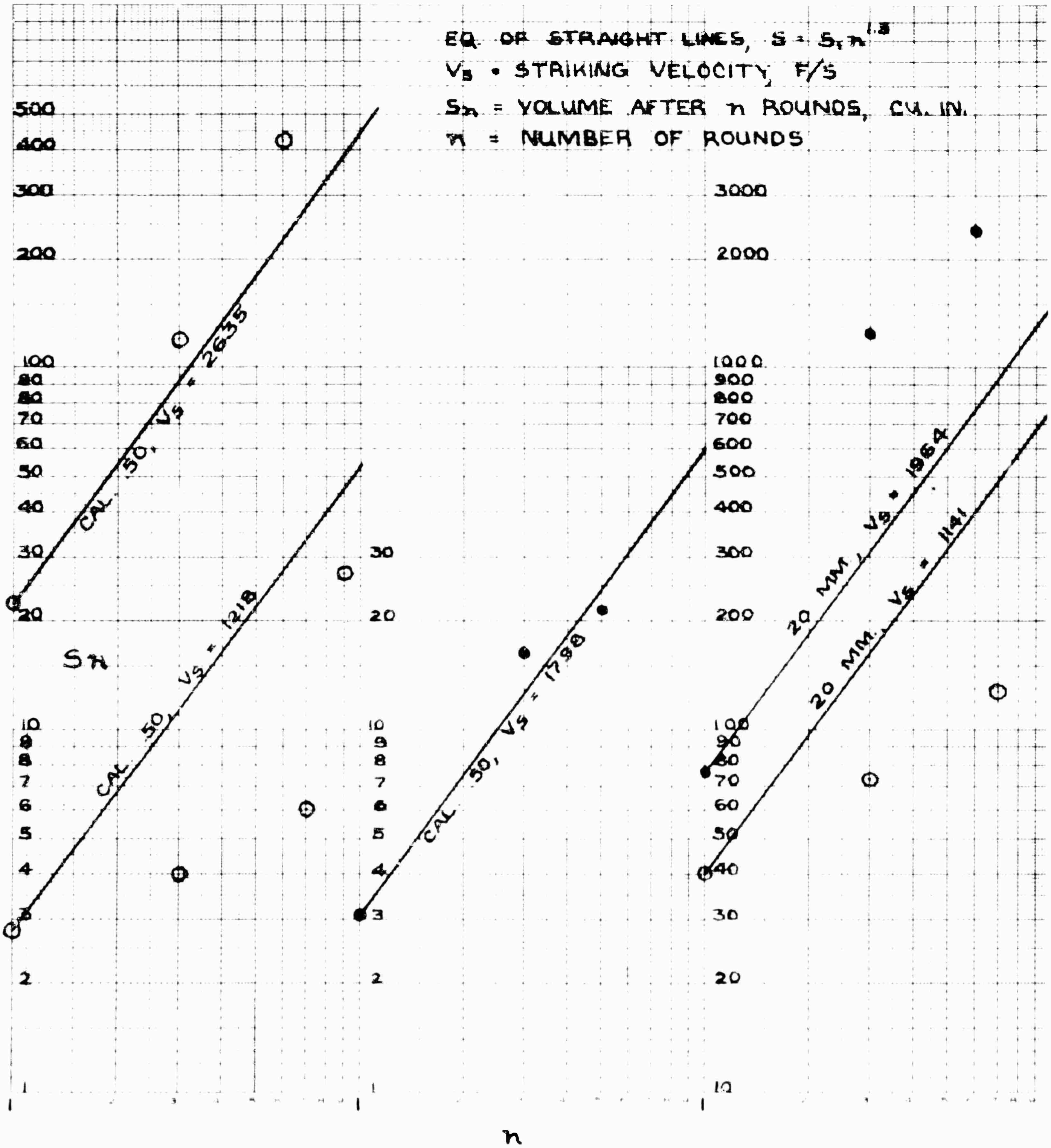
PLOT 24 - K"/W VS d FOR SANDSTONE



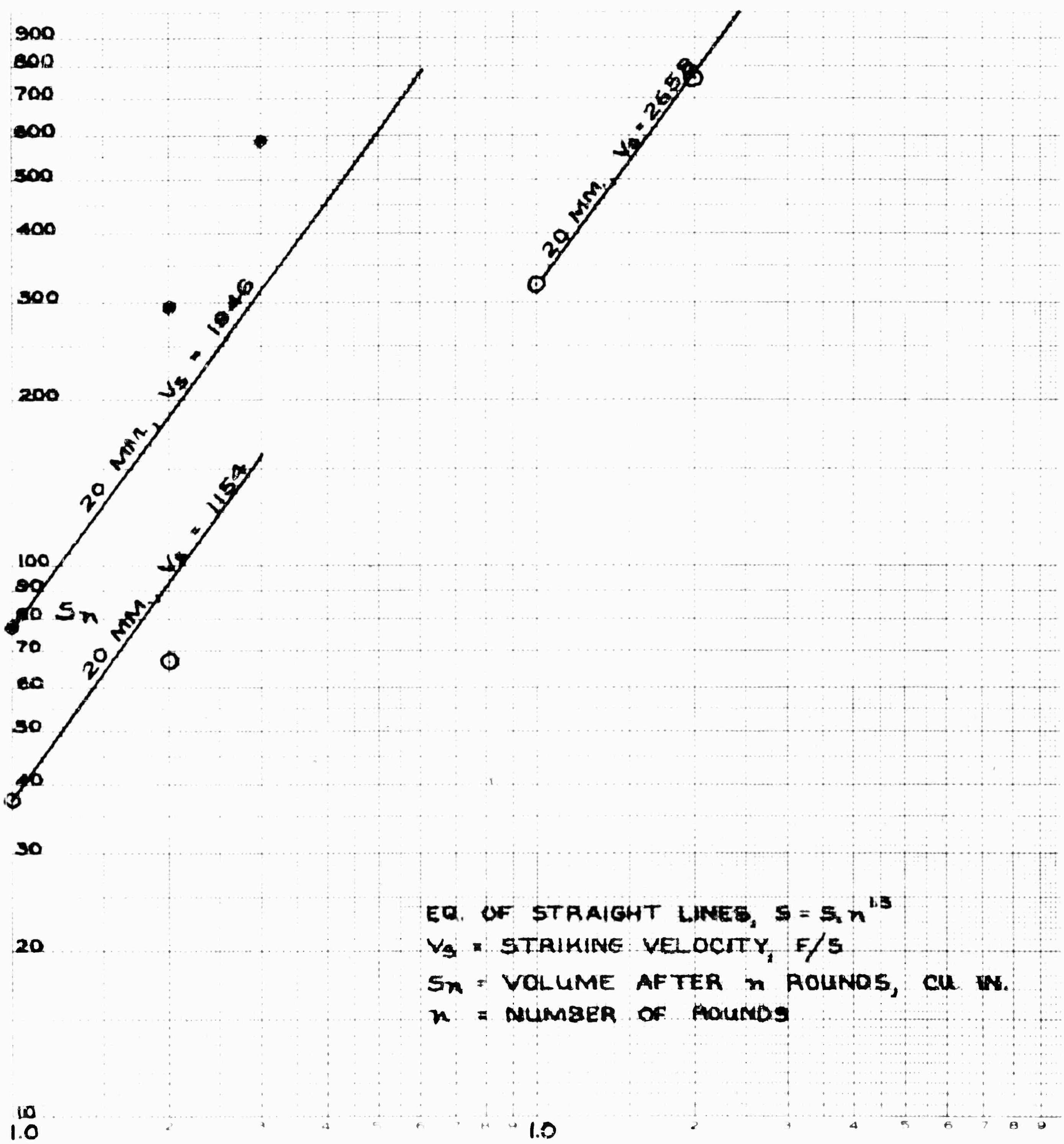
PLOT 25 CRATER VOLUMES IN REPEATED ROUNDS, FIRED INTO GRANITE.



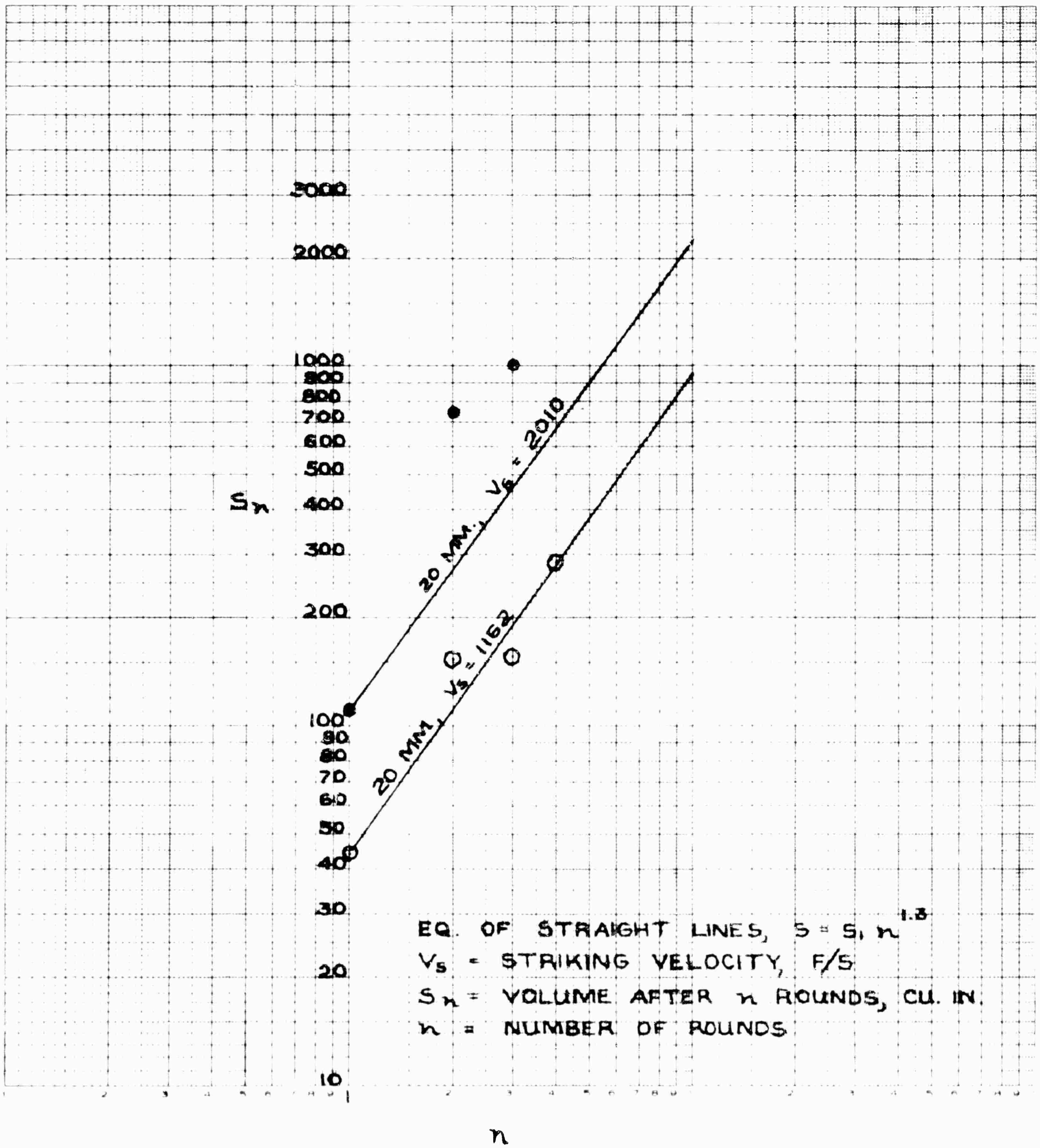
PLOT 26. CRATER VOLUME IN REPEATED ROUNDS, FIRED INTO DIABASE.



PLOT 27 CRATER VOLUME IN REPEATED ROUNDS, FIRED INTO QUARTZITE.



PLOT 28 CRATER VOLUME IN REPEATED ROUNDS, FIRED INTO INDIANA LIMESTONE



PLOT 29 CRATER VOLUME IN REPEATED ROUNDS, FIRED INTO SANDSTONE.