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TABLES AND GRAPHS OF THE THEORETICAL PEAK PRESSURES, ENERGIES,
AND POSITIVE IMPULSES OF BLAST WAVES IN AIR

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by

Stuart R. Brinkley, Jr., and John G. Kirkwood

Cornell University

NDRC Report No. A-327
OSRD Report No. 5137

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TABLES AND GRAPHS OF THE THEORETICAL PEAK PRESSURES, ENERGIES,
AND POSITIVE IMPULSES OF BLAST WAVES IN AIR

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Stuart R. Brinkley, Jr., and John G. Kirkwood
Cornell University

NDRC Report No. A-327
OSRD Report No. 5137

Submitted by

J. G. Kirkwood
John G. Kirkwood
Cornell University

Approved on May 28, 1945
for submission to the Committee

E. Bright Wilson, Jr.
E. Bright Wilson, Jr., Chief
Division 2
Effects of Impact and Explosion

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Preface

The work described in this report is pertinent to the project designated by the War Department Liaison Officer as OD-03 and to the project designated by the Navy Department Liaison Officer as NO-224. The report constitutes a progress report under Contract OEMsr-121 with Cornell University.

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TABLES AND GRAPHS OF THE THEORETICAL PEAK PRESSURES, ENERGIES,
AND POSITIVE IMPULSES OF BLAST WAVES IN AIR

Abstract

A theory of the propagation of shock waves from explosive sources was presented in OSRD Report No. 4814. In that report, a pair of ordinary differential equations for peak pressure and shock-wave energy as functions of the distance from the source were formulated from the equations of hydrodynamics by imposing a similarity restraint on the shape of the energy-time curve of the shock wave. Two-parameter families of peak pressure-distance, shock-wave energy-distance, and positive impulse-distance curves are obtained by the solution of these propagation equations. The parameters are conveniently chosen as the initial values of the pressure and shock-wave energy.

In the present report, tables and graphs of the two-parameter families of curves for blast waves from explosive sources in air are presented. A method is outlined for the determination of the parameters from experimental values of the peak pressure and positive impulse over a limited range of distances from the source. Estimates of the properties of the blast wave produced by TNT are obtained in this manner, and tentative peak pressure-distance and impulse-distance curves for all distances from the charge are constructed.

I. DESCRIPTION OF THE TABLES AND GRAPHS OF THE PROPERTIES OF
BLAST WAVES IN AIR

1. Introduction

A theory of propagation of shock waves from explosive sources has been described in an earlier report.^{1/} A pair of ordinary differential equations for peak pressure and shock-wave energy as functions of distance from the source were obtained from the equations of hydrodynamics and the Hugoniot relations by imposing a similarity restraint on the shape of the energy-time curve and by utilizing the second law of thermodynamics to determine, at an arbitrary distance, the distribution of the initial energy input from the explosive between energy available for further propagation and dissipated energy residual in the fluid already traversed by the shock wave. The theory takes

^{1/} Theory of the propagation of shock waves from explosive sources in air and water, by J. G. Kirkwood and S. R. Brinkley, Jr., NDRC Report A-318 (OSRD-4814).

proper account of the finite entropy increment in the fluid resulting from the passage of the shock wave and permits the use of the exact Hugoniot curve for the fluid.

The basic equations of the theory are

$$\left. \begin{aligned} \frac{dp}{dR} + \frac{p}{R} n(p) &= -\left(1 - \frac{1}{3} e^{-p}\right) \frac{R^2 p^4}{K} F(p), \\ \frac{dK}{dR} &= -p^3 R^2 f(p), \end{aligned} \right\} \quad (1)$$

where

$$\begin{aligned} f(p) &= \frac{12\gamma^3}{\gamma+1} \frac{h}{c_0^2 p^3}, \\ F(p) &= \frac{12G}{p} \frac{\gamma}{\gamma+1} \left(\frac{c_0}{U}\right)^2 \frac{1}{2(1+g)-G}, \\ n(p) &= \frac{4(\rho_0/\rho) + 2(1 - \rho_0/\rho)G}{2(1+g)-G}, \\ G &= 1 - \left(\frac{\rho_0 U}{\rho c}\right)^2, \quad g = 1 - \frac{p}{U} \frac{dU}{dp}, \end{aligned}$$

and p is the excess peak pressure measured in units of the pressure p_0 of the undisturbed air ahead of the shock wave, at a distance $R a_0$ from the center of a spherical charge of explosive of radius a_0 . The quantities ρ and ρ_0 are the densities of the air at distances R and infinity, respectively, c and c_0 denote the sound velocity in air at densities ρ and ρ_0 , respectively, U is the velocity of the shock front, and γ is the ratio of the heat capacities of air at a pressure p_0 and temperature of 300°K , h is the specific enthalpy increment of an element of fluid, traversed by a shock wave of peak pressure p , after return to pressure p_0 along its new adiabetic. The variable K is related to the shock-wave energy ξ per gram of the initial explosive charge by

$$\xi = \frac{\gamma+1}{4\gamma^2} \frac{p_0}{\rho_e} K, \quad (2)$$

where ρ_e is the density of loading of the explosive. The positive impulse is given by

$$I = \left(1 - \frac{1}{2} e^{-\sqrt{p}}\right) \frac{p_0 p a_0}{c_0} \left\{ \frac{1}{R} \alpha(p) + \frac{R^2}{K} \beta(p) \right\}^{-1}, \quad (3)$$

where

$$\alpha(p) = 2 \frac{U}{c_0} \left\{ \left(\frac{p}{p_0} - 1 \right) \left[\frac{1 + g - (1 - \rho_0/\rho)G}{2(1 + g) - G} \right] + \frac{2(\rho_0/\rho) - 1}{2(1 + g) - G} \right\},$$

$$\beta(p) = \frac{12\gamma}{\gamma + 1} \left(1 - \frac{1}{3} e^{-p} \right) \frac{p^2 (\rho/\rho_0)}{(U/c_0)} \left\{ \frac{1 + g - (1 - \rho_0/\rho)G}{2(1 + g) - G} \right\}.$$

Tables of functions which are closely related to those defined in Eqs. (1) and (3) have been presented in the earlier report.^{1/}

2. Description of the tables and graphs

The two-parameter family of peak pressure-distance curves and the family of shock-wave energy-distance curves for selected values of the constants of integration were obtained by numerical integration of Eqs. (1), employing the methods of Part III of the previous report.^{1/} Each member of the two families is characterized by a value of p_1 , the excess peak pressure at the initial instant of time measured in units of p_0 , and by a value of Q_1 , related to the initial shock-wave energy ξ_1 by

$$Q_1 = \frac{4\gamma^2}{\gamma + 1} \frac{\rho_e \xi_1}{p_0 p_1}. \quad (4)$$

The family of peak pressure-distance curves is presented in tabular form in Table I. In this and following tables, a reduced distance variable equal to $R(\rho_e/W)^{1/3}$ is employed, where R is expressed in feet, ρ_e in grams per cubic centimeter, and W in pounds. In order to facilitate interpolation with respect to distance, the entries of the table are of the function $pR(\rho_e/W)^{1/3}$ with p expressed in pounds per square inch.^{2/}

Portions of the peak pressure-distance curves for moderately large distances are presented in a series of graphs, Figs. 1 to 7. Each graph gives a family of peak pressure-distance curves for a fixed value of the parameter Q_1 , plotted as $\log pR(\rho_e/W)^{1/3}$ versus $\log R(\rho_e/W)^{1/3}$. These graphs are designed to aid in the determination of the parameters from an experimental peak pressure-distance curve in a manner to be described in the following.

^{2/} Note that in the tables p is expressed in pounds per square inch, while in the equations p was a dimensionless quantity expressed in units of p_0 .

The family of shock-wave energy-distance curves is tabulated in Table II, the entries of which are $\rho_e \xi$ with the reduced distance defined in the foregoing as argument. The units of ξ are calories per gram of explosive.

The family of positive impulse-distance curves was constructed with the aid of Eqs. (3), and it is tabulated in Table III. Here, the function $10^3 IR(\rho_e/W)^{2/3}$ is listed with the reduced distance as argument. The units of I are pound second per square inch. Portions of these curves for moderately large distances are presented in the series of graphs, Figs. 8 to 14. These graphs are analogous to those for the peak pressure, with the function $10^3 IR(\rho_e/W)^{2/3}$ being plotted against $\log R(\rho_e/W)^{1/3}$ for fixed values of the parameter Q_1 . They will be useful in the determination of the initial parameters from experimental values of the positive impulse.

3. Determination of the initial parameters from experimental data

The graphs, Figs. 1 to 14 are designed to aid in the determination of the parameters of those members of the families of peak-pressure and positive-impulse curves that give the best fit to a particular set of experimental data. For this purpose, the experimental data may be plotted to the correct scale on tracing cloth and compared with the theoretical values by superimposing the tracing on the published graphs. Unless the data are of high accuracy, this procedure will not lead to a unique determination of the parameters but to the selection of several pairs of values of the parameters between which a choice could not easily be made by visual methods. The method of least squares may then be used to narrow the choice of parameters. One computes the mean of the squares of the weighted deviations of the individual experimental values of the peak pressure and positive impulse from the theoretical values given by the curves selected by visual matching, employing the reciprocal of the root mean square deviations of the experimental points at a given distance from their mean as the weight factor at that distance. One then selects the parameter set yielding the smallest value of this quantity for both peak pressure and impulse.^{3/}

^{3/} See E. T. Whittaker and G. Robinson, The calculus of observations, 3rd edition (Blackie and Son, 1940), pp. 182, 221.

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We have employed the method outlined to obtain estimates of the properties of the blast wave of TNT. The results are presented in Part III of this report. They will serve to illustrate the method of curve fitting which is proposed.

It should be noted that results of high accuracy can not be obtained in this manner. Thus the procedure is numerically unfavorable for the prediction of effects close to the charge. It is believed that thermodynamic estimates of the initial pressure, on which calculations are now in progress, will greatly increase the accuracy with which the parameters may be fixed.

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C O N F I D E N T I A L

II. TABLES AND GRAPHS OF THE PEAK PRESSURE, ENERGY, AND
POSITIVE IMPULSE FOR BLAST WAVES IN AIR

Symbols and Units

<u>Symbol</u>	<u>Unit</u>	<u>Definition</u>
R	ft	Distance from the center of spherical charge of explosive.
ρ_e	gm/cm ³	Density of explosive.
W	lb	Weight of charge of explosive.
p	lb/in ²	Excess peak pressure of blast wave.
p ₁	--	Initial excess peak pressure [$= p_{\text{initial}}/p_0$].
p ₀	lb/in ²	Pressure of the undisturbed air ahead of the blast wave.
Q ₁	--	Initial value of reduced energy variable.
ξ	cal/gm	Shock-wave energy.
I	lb-sec/in ²	Positive impulse of blast wave.

Note: The first tabulated value of the distance argument, $(\rho_e/W)^{1/3} = 0.156$, corresponds to the surface of the sphere of intact explosive.

C O N F I D E N T I A L

Table I. The peak pressure.

$(\rho_e/w)^{1/3} R$	$(\rho_e/w)^{1/3} R_p$							
	Q_1 P_1	200	250	300	350	400	450	500
0.156	500	1130	1130	1130	1130	1130	1130	1130
	600	1360	1360	1360	1360	1360	1360	1360
	700	1590	1590	1590	1590	1590	1590	1590
	800	1810	1810	1810	1810	1810	1810	1810
	900	2040	2040	2040	2040	2040	2040	2040
	1000	2270	2270	2270	2270	2270	2270	2270
0.2	500	1130	1130	1130	1130	1130	1130	1130
	600	1360	1360	1360	1360	1360	1360	1360
	700	1580	1580	1590	1590	1590	1590	1590
	800	1810	1820	1820	1820	1820	1820	1820
	900	2040	2040	2040	2040	2040	2050	2050
	1000	2260	2260	2270	2270	2270	2270	2270
0.3	500	1120	1120	1130	1130	1130	1130	1140
	600	1340	1340	1350	1350	1360	1360	1360
	700	1560	1570	1580	1580	1580	1580	1580
	800	1790	1800	1800	1810	1810	1810	1810
	900	2010	2020	2030	2030	2040	2040	2040
	1000	2230	2240	2250	2260	2260	2260	2270
0.5	500	1060	1080	1090	1100	1110	1110	1120
	600	1270	1290	1310	1320	1330	1330	1330
	700	1480	1500	1520	1540	1550	1550	1560
	800	1690	1720	1740	1760	1770	1780	1780
	900	1900	1940	1960	1970	1990	2000	2010
	1000	2110	2150	2180	2190	2210	2220	2230
0.7	500	983	1020	1040	1060	1070	1080	1090
	600	1170	1210	1240	1260	1280	1290	1300
	700	1360	1410	1440	1460	1480	1500	1510
	800	1560	1600	1640	1680	1700	1710	1730
	900	1750	1810	1850	1880	1910	1930	1940
	1000	1940	2010	2050	2090	2120	2140	2150
1.0	500	845	899	938	967	990	1010	1020
	600	1010	1070	1120	1150	1180	1200	1220
	700	1170	1240	1300	1340	1370	1400	1420
	800	1330	1410	1480	1520	1560	1590	1610
	900	1480	1580	1650	1710	1750	1790	1810
	1000	1640	1760	1830	1880	1940	1980	2020
1.5	500	614	687	744	790	828	860	885
	600	728	816	885	940	986	1020	1060
	700	841	944	1020	1090	1140	1190	1220
	800	954	1070	1160	1240	1300	1350	1390
	900	1060	1200	1300	1380	1450	1510	1560
	1000	1110	1320	1440	1530	1610	1670	1720

Table I. [Concluded.]

$(\rho_e/W)^{1/3} R$	$(\rho_e/W)^{1/3} R_p$							
	Q_1 P_1	200	250	300	350	400	450	500
2.0	500	433	506	568	620	664	704	736
	600	510	598	671	734	788	834	874
	700	586	688	775	848	910	964	1010
	800	662	779	877	960	1030	1090	1150
	900	737	868	979	1070	1150	1220	1280
	1000	810	955	1080	1180	1270	1350	1420
3.0	500	228	280	329	374	415	453	488
	600	263	326	384	437	487	532	573
	700	298	371	438	500	557	610	658
	800	333	415	492	562	628	688	743
	900	368	459	544	623	697	764	826
	1000	401	502	597	685	765	841	909
5.0	500	103	125	147	169	191	212	233
	600	114	140	165	191	217	242	267
	700	124	153	183	212	241	270	299
	800	134	167	200	233	266	299	331
	900	144	180	216	253	290	327	362
	1000	154	193	233	273	314	354	394
7.0	500	71.5	84.4	97.2	110	122	134	147
	600	77.4	91.9	106	120	134	148	163
	700	82.6	98.8	115	130	146	162	178
	800	88.0	105	123	140	157	175	193
	900	92.8	112	130	149	168	188	207
	1000	97.4	118	138	158	179	200	221
10	500	54.2	62.7	70.9	78.8	86.4	93.8	101
	600	57.9	67.2	76.1	84.7	93.1	101	110
	700	61.2	71.2	80.7	90.2	99.4	108	117
	800	64.3	74.9	85.2	95.4	105	115	125
	900	67.1	78.5	89.4	100	110	121	132
	1000	69.9	81.8	93.4	105	116	127	138
15	500	43.2	49.1	54.9	60.3	65.3	70.3	75.1
	600	45.8	52.2	58.4	64.0	69.6	75.0	80.2
	700	48.0	54.9	61.3	67.4	73.4	79.1	84.8
	800	50.1	57.3	64.0	70.6	76.9	83.0	88.8
	900	52.0	59.6	66.7	73.5	80.0	86.7	92.7
	1000	53.7	61.6	69.1	76.3	83.1	89.8	96.5
20	500	37.8	42.9	47.7	52.1	56.3	60.5	64.2
	600	40.0	45.4	50.5	55.1	59.8	64.0	68.2
	700	41.9	47.7	52.9	57.9	62.6	67.2	71.6
	800	43.5	49.5	55.0	60.4	65.4	70.1	74.6
	900	45.2	51.4	57.1	62.6	67.6	72.9	77.6
	1000	46.6	53.0	59.0	64.7	70.1	75.2	80.3
30	500	31.8	36.0	40.0	43.5	46.9	50.2	53.3
	600	33.6	38.0	42.2	45.9	49.7	53.1	56.4
	700	35.1	39.8	44.2	48.2	51.9	55.6	58.6
	800	36.5	41.4	45.8	50.2	54.0	57.7	61.6
	900	37.8	42.8	47.4	51.8	55.7	60.2	63.6
	1000	38.9	44.1	48.9	53.5	57.7	61.6	65.5

Table II. The shock-wave energy.

$(\rho_e/W)^{1/3} R$	$\rho_e \epsilon$							
	Q_1 P_1	200	250	300	350	400	450	500
0.156	500	731	914	1100	1280	1460	1650	1830
	600	877	1100	1320	1540	1750	1970	2190
	700	1020	1280	1540	1790	2050	2300	2560
	800	1170	1460	1750	2050	2340	2630	2920
	900	1320	1650	1970	2300	2630	2960	3290
	1000	1460	1830	2190	2560	2920	3290	3660
0.2	500	729	911	1100	1280	1460	1640	1820
	600	874	1090	1310	1530	1750	1970	2190
	700	1020	1280	1530	1790	2040	2300	2560
	800	1170	1460	1750	2040	2340	2630	2920
	900	1310	1640	1970	2300	2630	2960	3290
	1000	1460	1820	2190	2560	2920	3280	3650
0.3	500	722	905	1090	1270	1450	1630	1820
	600	865	1080	1300	1520	1740	1960	2180
	700	1010	1270	1520	1780	2030	2290	2540
	800	1150	1450	1740	2030	2320	2620	2910
	900	1300	1620	1960	2280	2610	2940	3280
	1000	1440	1810	2170	2540	2900	3270	3640
0.5	500	701	886	1060	1250	1430	1610	1800
	600	840	1060	1280	1500	1720	1940	2150
	700	979	1230	1490	1750	2000	2260	2510
	800	1120	1410	1700	1990	2290	2580	2870
	900	1260	1590	1910	2240	2570	2900	3230
	1000	1400	1760	2120	2490	2860	3220	3580
0.7	500	673	854	1030	1220	1410	1580	1760
	600	806	1020	1240	1460	1680	1900	2120
	700	939	1190	1450	1700	1960	2220	2470
	800	1070	1360	1650	1940	2240	2530	2820
	900	1200	1530	1850	2180	2510	2840	3160
	1000	1330	1700	2060	2430	2790	3160	3510
1.0	500	622	801	981	1160	1340	1520	1710
	600	746	960	1180	1390	1610	1830	2050
	700	868	1120	1370	1620	1880	2130	2380
	800	989	1270	1560	1850	2140	2440	2710
	900	1100	1430	1750	2080	2410	2730	3050
	1000	1230	1590	1940	2300	2670	3040	3400
1.5	500	526	696	869	1040	1220	1400	1580
	600	631	835	1040	1250	1460	1680	1890
	700	735	972	1210	1460	1710	1960	2210
	800	837	1110	1380	1660	1950	2230	2520
	900	939	1240	1550	1870	2190	2510	2830
	1000	1040	1380	1720	2070	2430	2780	3140
2.0	500	433	588	749	915	1080	1260	1430
	600	518	705	898	1100	1300	1500	1710
	700	604	822	1050	1270	1510	1750	2000
	800	689	941	1190	1460	1730	2000	2280
	900	774	1050	1340	1640	1940	2250	2560
	1000	858	1170	1490	1820	2150	2500	2840

Table II. [Concluded.]

$(\rho_e/W)^{1/3} R$	ρ_e							
	Q_1 P_1	200	250	300	350	400	450	500
3.0	500	291	412	542	679	823	972	1130
	600	349	493	649	813	986	1160	1350
	700	406	573	755	949	1150	1360	1570
	800	462	653	862	1080	1310	1550	1790
	900	518	734	968	1210	1470	1740	2020
	1000	574	815	1070	1350	1640	1920	2240
5.0	500	170	240	319	406	499	599	705
	600	198	282	376	478	590	709	835
	700	227	323	432	551	681	819	967
	800	255	364	487	624	771	929	1100
	900	282	404	543	695	858	1040	1230
	1000	310	445	598	768	952	1150	1360
7.0	500	127	177	233	294	361	432	507
	600	146	205	271	342	420	504	593
	700	165	232	307	389	479	574	678
	800	184	259	343	436	537	645	761
	900	202	285	379	481	591	715	844
	1000	220	311	414	527	650	785	930
10	500	98.2	136	178	222	270	322	377
	600	113	156	204	255	312	371	434
	700	127	176	229	288	351	418	490
	800	140	194	254	320	390	465	545
	900	153	212	279	350	426	510	599
	1000	165	230	302	380	464	536	654
15	500	78.1	106	138	171	206	245	285
	600	89.2	121	158	194	236	281	327
	700	99.9	137	176	219	264	314	366
	800	109	149	192	242	293	345	402
	900	119	162	210	262	316	379	441
	1000	127	174	227	283	343	408	478
20	500	68.4	92.8	120	148	177	210	243
	600	78.1	106	137	167	203	240	279
	700	87.0	118	152	188	225	267	310
	800	94.6	129	165	207	250	291	337
	900	103	139	180	223	267	319	370
	1000	110	150	194	240	289	341	397
30	500	57.6	78.0	100	123	148	175	202
	600	65.2	88.4	114	140	168	199	230
	700	72.6	98.5	126	156	187	221	253
	800	79.3	107	137	172	206	240	278
	900	86.0	116	149	184	220	263	303
	1000	92.1	126	160	198	238	279	323

Table III. The positive impulse.

$(\rho_e/W)^{1/3} R$	$10^3 (\rho_e/W)^{2/3} R I$							
	Q_1 P_1	200	250	300	350	400	450	500
0.156	500	1.29	1.30	1.30	1.30	1.31	1.31	1.31
	600	1.38	1.39	1.39	1.40	1.40	1.40	1.40
	700	1.48	1.48	1.49	1.49	1.50	1.50	1.50
	800	1.61	1.62	1.62	1.63	1.63	1.63	1.64
	900	1.76	1.77	1.78	1.78	1.79	1.79	1.79
	1000	1.93	1.94	1.95	1.95	1.96	1.96	1.96
0.2	500	1.90	1.92	1.93	1.94	1.95	1.95	1.95
	600	2.02	2.04	2.06	2.07	2.07	2.08	2.08
	700	2.14	2.16	2.18	2.18	2.19	2.20	2.20
	800	2.26	2.28	2.29	2.30	2.31	2.32	2.32
	900	2.38	2.40	2.42	2.43	2.44	2.44	2.45
	1000	2.55	2.57	2.59	2.60	2.61	2.62	2.62
0.3	500	3.56	3.63	3.68	3.72	3.75	3.77	3.79
	600	3.76	3.83	3.89	3.92	3.96	3.98	4.00
	700	3.94	4.03	4.09	4.12	4.16	4.18	4.20
	800	4.13	4.22	4.28	4.32	4.35	4.37	4.40
	900	4.30	4.39	4.46	4.50	4.53	4.56	4.58
	1000	4.47	4.56	4.63	4.67	4.71	4.73	4.76
0.5	500	7.44	7.80	8.06	8.26	8.42	8.54	8.64
	600	7.74	8.11	8.38	8.60	8.76	8.90	9.00
	700	8.06	8.45	8.74	8.96	9.12	9.26	9.36
	800	8.30	8.72	9.01	9.23	9.42	9.55	9.68
	900	8.57	9.00	9.30	9.54	9.72	9.86	10.0
	1000	8.84	9.28	9.60	9.85	10.0	10.2	10.3
0.7	500	11.0	11.9	12.5	13.1	13.5	13.8	14.1
	600	11.5	12.4	13.1	13.6	14.1	14.5	14.8
	700	12.0	12.9	13.6	14.1	14.6	15.0	15.3
	800	12.3	13.2	14.0	14.6	15.0	15.4	15.8
	900	12.6	13.6	14.4	15.0	15.5	15.9	16.2
	1000	13.0	14.0	14.7	15.4	15.9	16.3	16.7
1.0	500	15.1	16.8	18.3	19.5	20.5	21.4	22.2
	600	15.8	17.6	19.1	20.3	21.4	22.3	23.1
	700	16.4	18.3	19.8	21.1	22.2	23.1	23.9
	800	17.0	18.8	20.4	21.7	22.9	23.8	24.7
	900	17.4	19.4	21.0	22.4	23.5	24.6	25.4
	1000	17.9	19.9	21.5	22.9	24.2	25.2	26.1
1.5	500	18.8	21.6	24.1	26.4	28.4	30.3	32.0
	600	19.8	22.8	25.5	27.8	30.0	31.9	33.6
	700	20.7	23.9	26.6	29.1	31.3	33.3	35.1
	800	21.6	24.8	27.3	30.2	32.4	34.5	36.3
	900	22.4	25.6	28.6	31.1	33.4	35.5	37.4
	1000	23.0	26.4	29.3	32.0	34.3	36.5	38.4

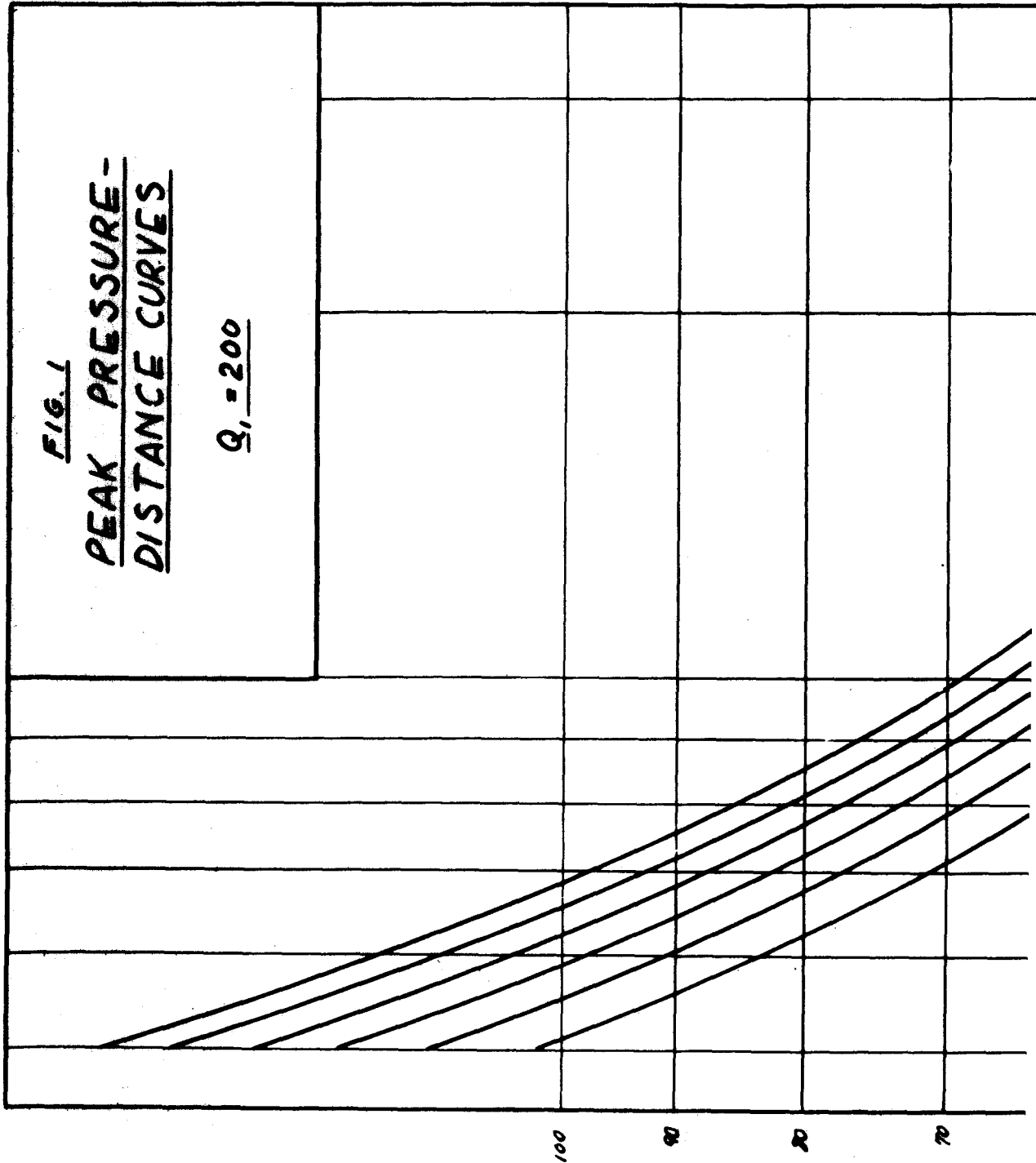
Table III. [Concluded.]

$(\rho_e/W)^{1/3} R$	$10^3 (\rho_e/W)^{2/3} R$							
	Q_1 p_1	200	250	300	350	400	450	500
2.0	500	20.8	24.2	27.4	30.2	33.0	35.5	37.9
	600	22.0	25.6	28.9	32.0	34.8	37.4	39.9
	700	23.0	26.8	30.3	33.5	36.4	39.2	41.8
	800	24.0	28.0	31.5	34.9	37.9	40.8	43.5
	900	24.9	28.9	32.7	36.1	39.3	42.3	45.0
	1000	25.7	29.9	33.7	37.2	40.6	43.6	46.4
3.0	500	23.4	27.3	31.0	34.6	38.0	41.2	44.6
	600	24.8	28.9	32.8	36.6	40.1	43.6	46.8
	700	26.0	30.3	34.4	38.3	42.0	45.6	49.1
	800	27.0	31.6	35.9	40.0	43.8	47.6	51.1
	900	28.0	32.8	37.2	41.4	45.4	49.3	52.9
	1000	29.0	33.9	38.5	42.8	47.0	50.9	54.8
5.0	500	30.1	34.5	38.6	42.0	45.7	49.5	53.0
	600	31.6	36.2	40.4	44.1	48.2	51.9	55.5
	700	33.0	37.4	41.7	46.1	50.2	54.0	57.8
	800	34.1	38.6	43.2	47.8	51.9	56.0	60.1
	900	35.1	39.8	44.7	49.2	53.2	57.6	61.9
	1000	35.9	41.0	46.1	50.6	55.2	59.6	64.0
7.0	500	35.3	40.7	45.7	50.3	54.5	58.7	62.7
	600	37.2	43.0	48.1	52.7	57.3	61.7	65.7
	700	39.1	44.9	50.0	55.0	59.7	64.2	68.4
	800	40.7	46.5	51.9	57.2	61.9	66.4	70.6
	900	42.0	48.0	53.7	58.9	63.6	68.1	72.8
	1000	43.3	49.5	55.3	60.6	65.4	70.3	74.5
10	500	33.9	45.7	52.2	53.0	63.3	68.7	73.8
	600	41.3	48.7	55.4	61.2	67.2	72.6	77.8
	700	43.8	51.4	58.1	63.8	70.4	76.1	81.5
	800	45.8	53.6	60.5	67.3	73.4	79.0	84.7
	900	47.7	55.6	62.9	69.8	75.9	82.0	87.6
	1000	49.5	57.4	65.1	72.0	78.3	84.6	90.4
15	500	41.6	49.5	56.8	63.9	70.5	77.1	82.9
	600	44.5	53.0	60.6	68.1	75.3	82.1	87.9
	700	47.2	56.6	64.6	72.4	79.2	86.1	92.1
	800	49.6	59.0	67.4	75.8	83.0	89.4	96.1
	900	52.0	61.4	70.4	78.5	85.5	92.7	100
	1000	53.8	64.0	72.9	80.9	88.5	96.2	104
20	500	42.4	50.7	58.1	65.3	72.6	79.2	86.2
	600	45.2	54.4	62.0	69.4	77.6	85.3	92.9
	700	48.0	58.0	65.8	74.0	81.7	90.5	98.0
	800	50.4	60.4	68.7	78.1	86.6	94.3	103
	900	52.8	63.0	72.2	81.2	89.6	98.5	108
	1000	54.5	65.6	74.7	84.4	93.6	103	111
30	500	43.0	51.6	59.0	66.2	73.6	80.0	87.4
	600	45.8	55.4	62.8	70.4	78.6	86.3	96.6
	700	48.5	58.2	66.8	74.8	83.0	92.0	100
	800	50.8	61.8	68.6	78.8	88.0	95.9	105
	900	53.3	64.6	73.0	82.2	91.4	100	110
	1000	54.9	67.0	75.6	85.6	95.6	105	114

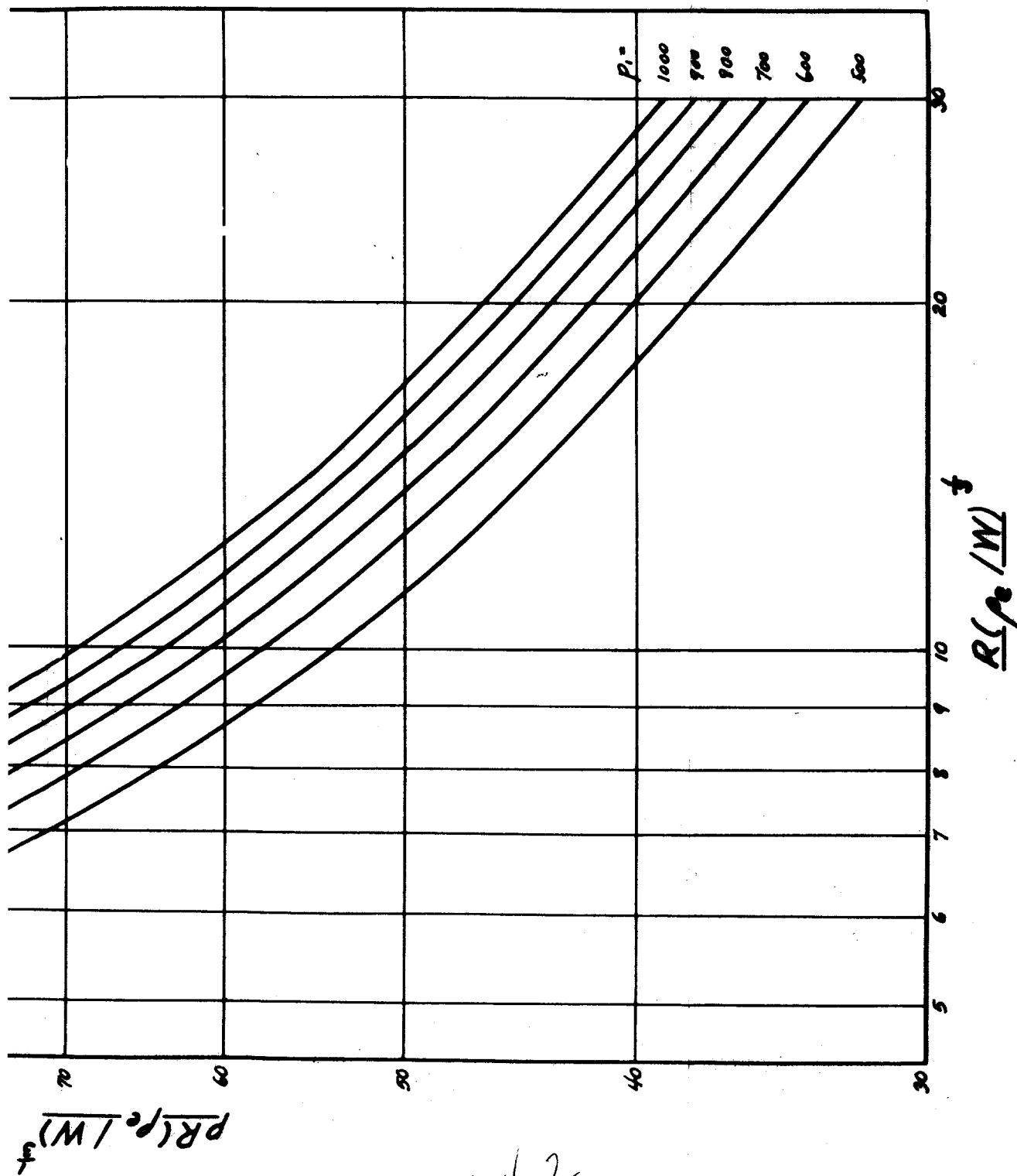
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FIG. 1
PEAK PRESSURE-
DISTANCE CURVES

$Q_1 = 200$



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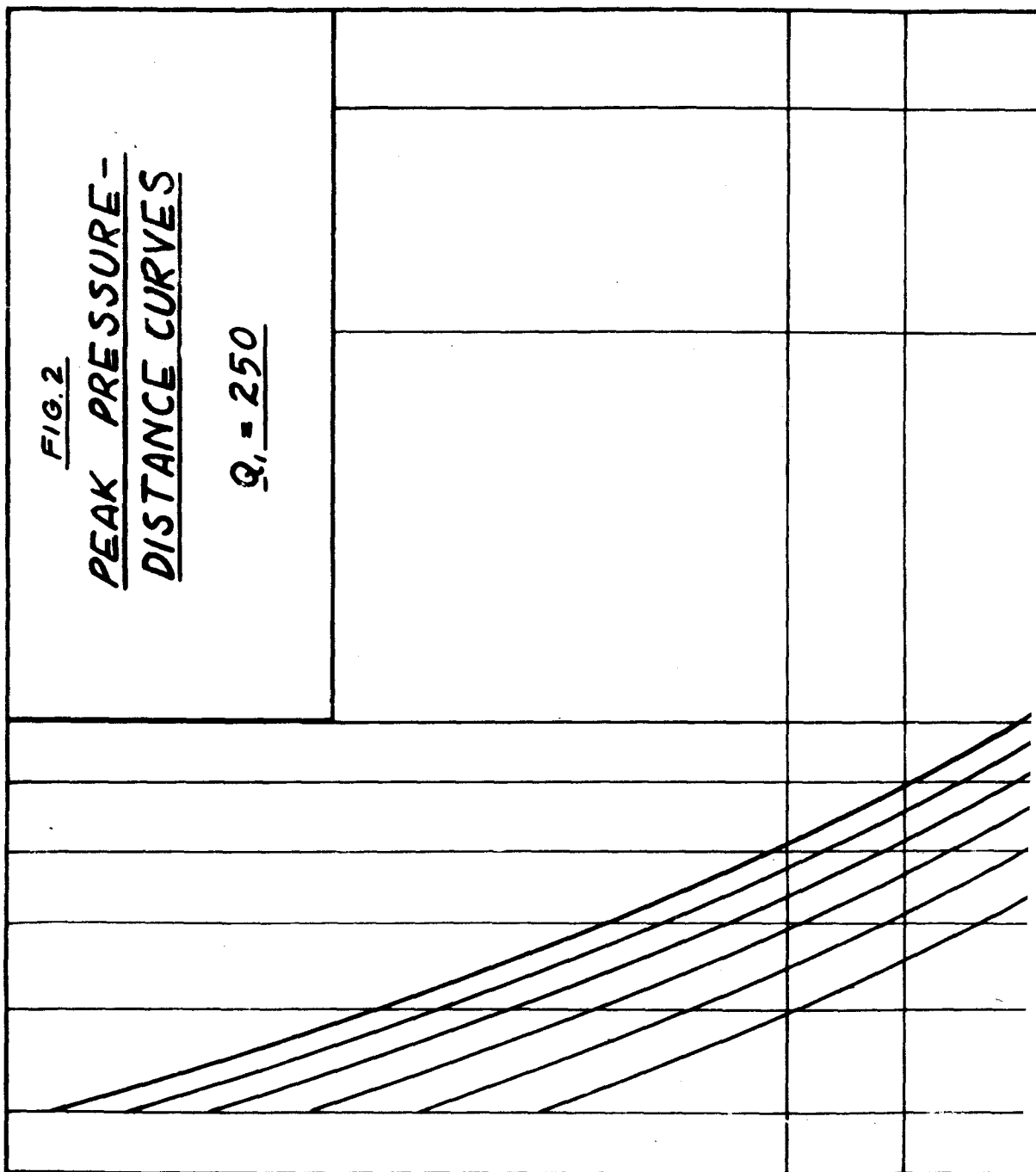
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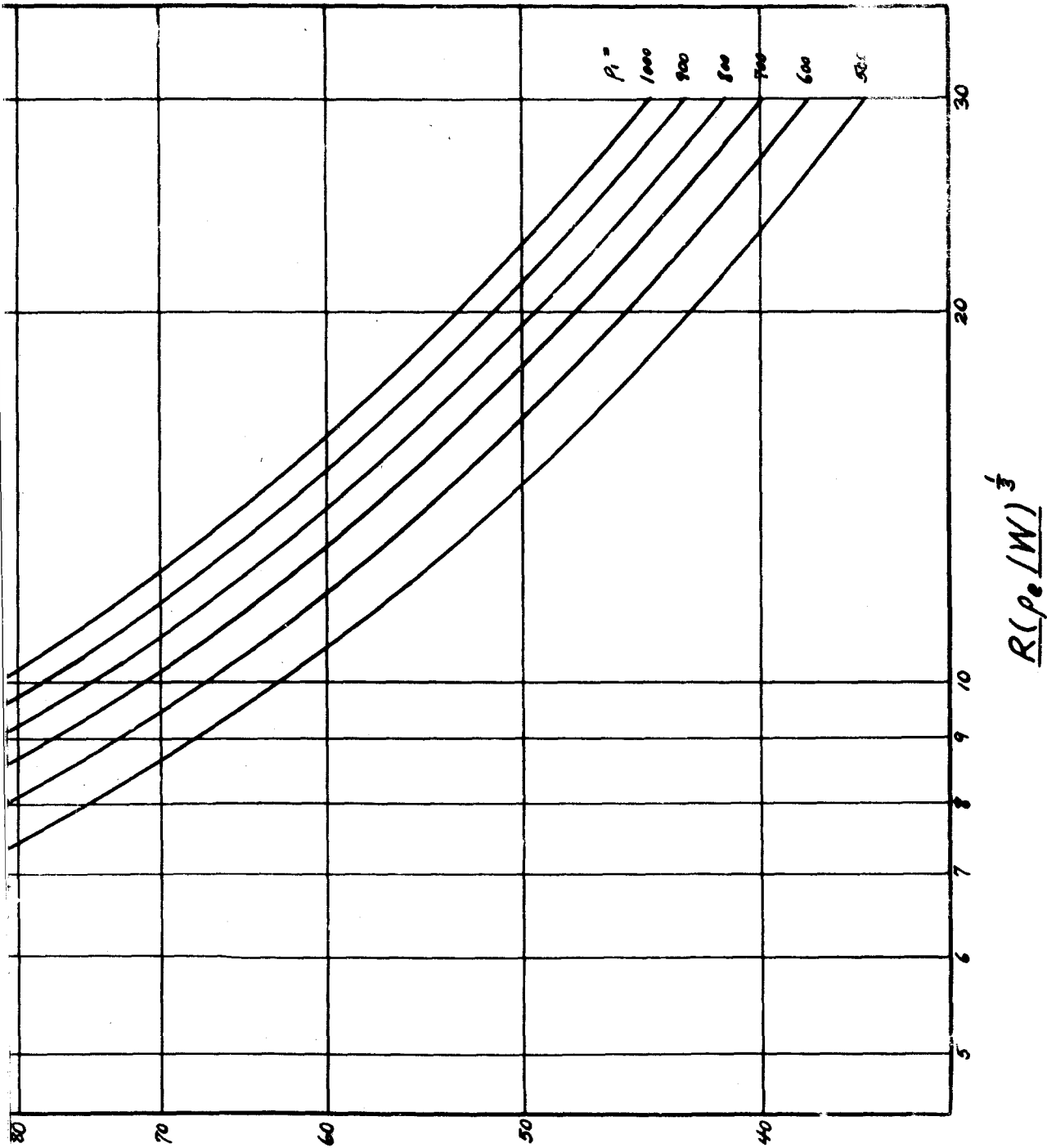
FIG. 2
PEAK PRESSURE-
DISTANCE CURVES

$Q_1 = 250$



1 2

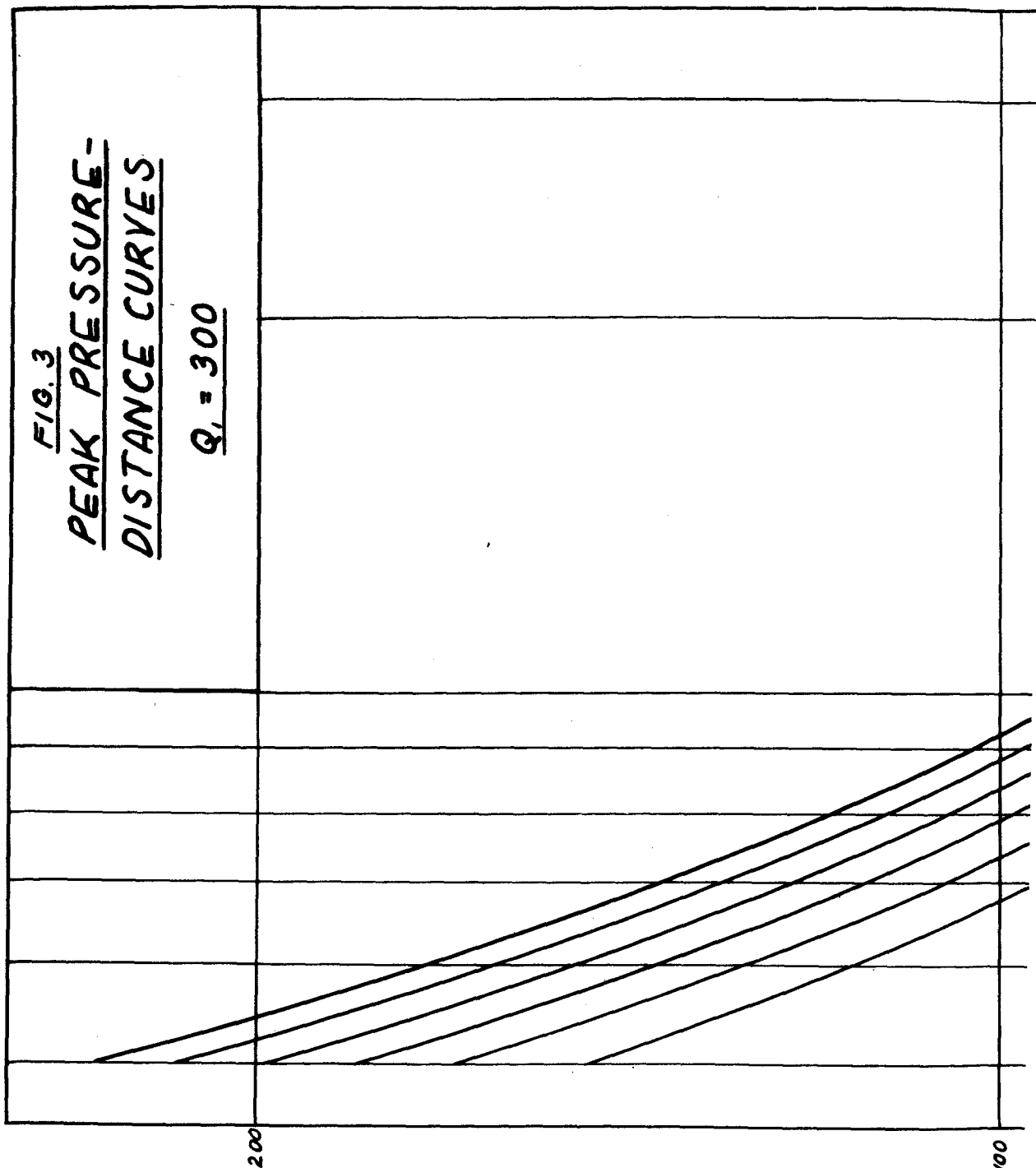
W
M

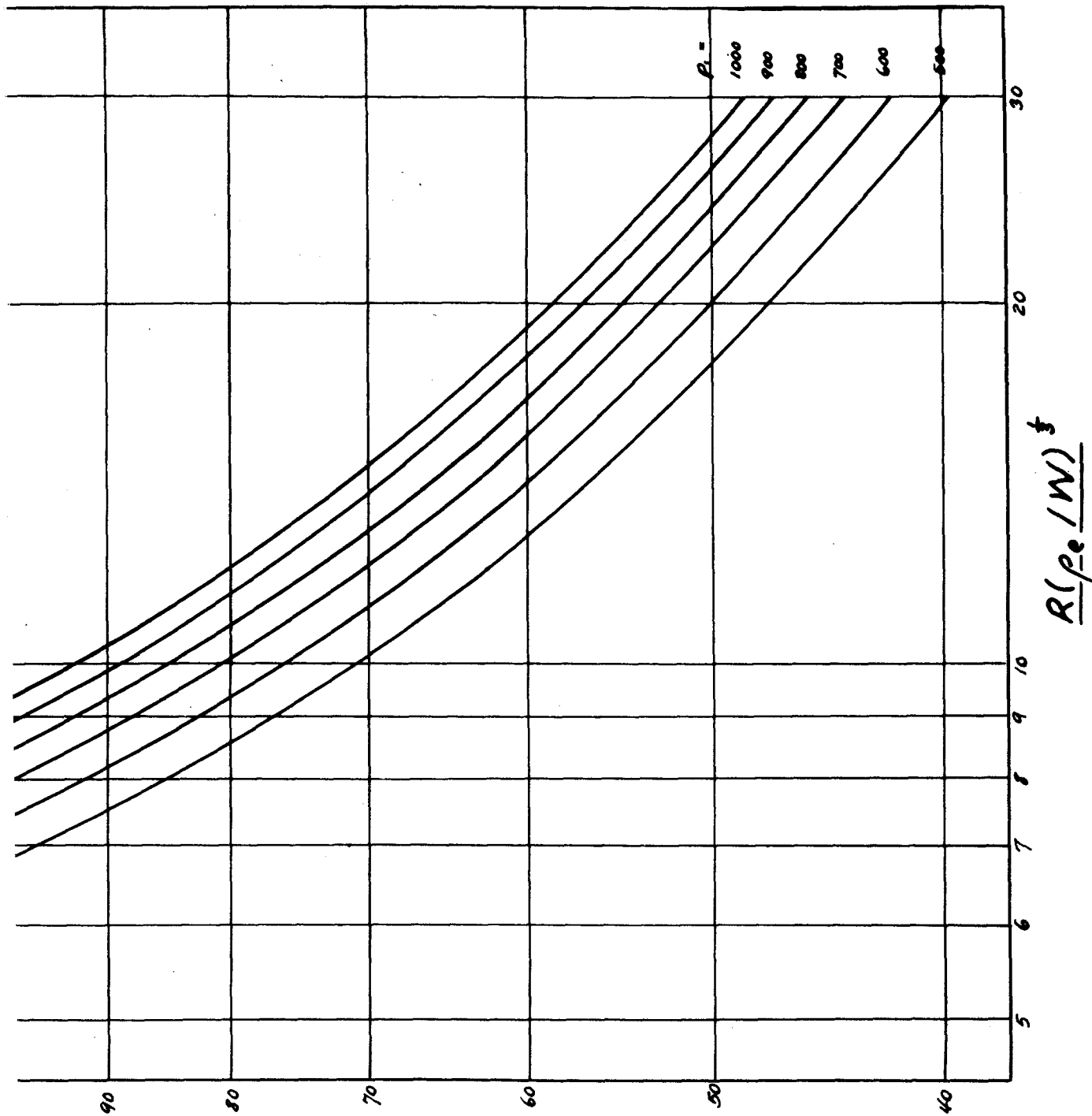


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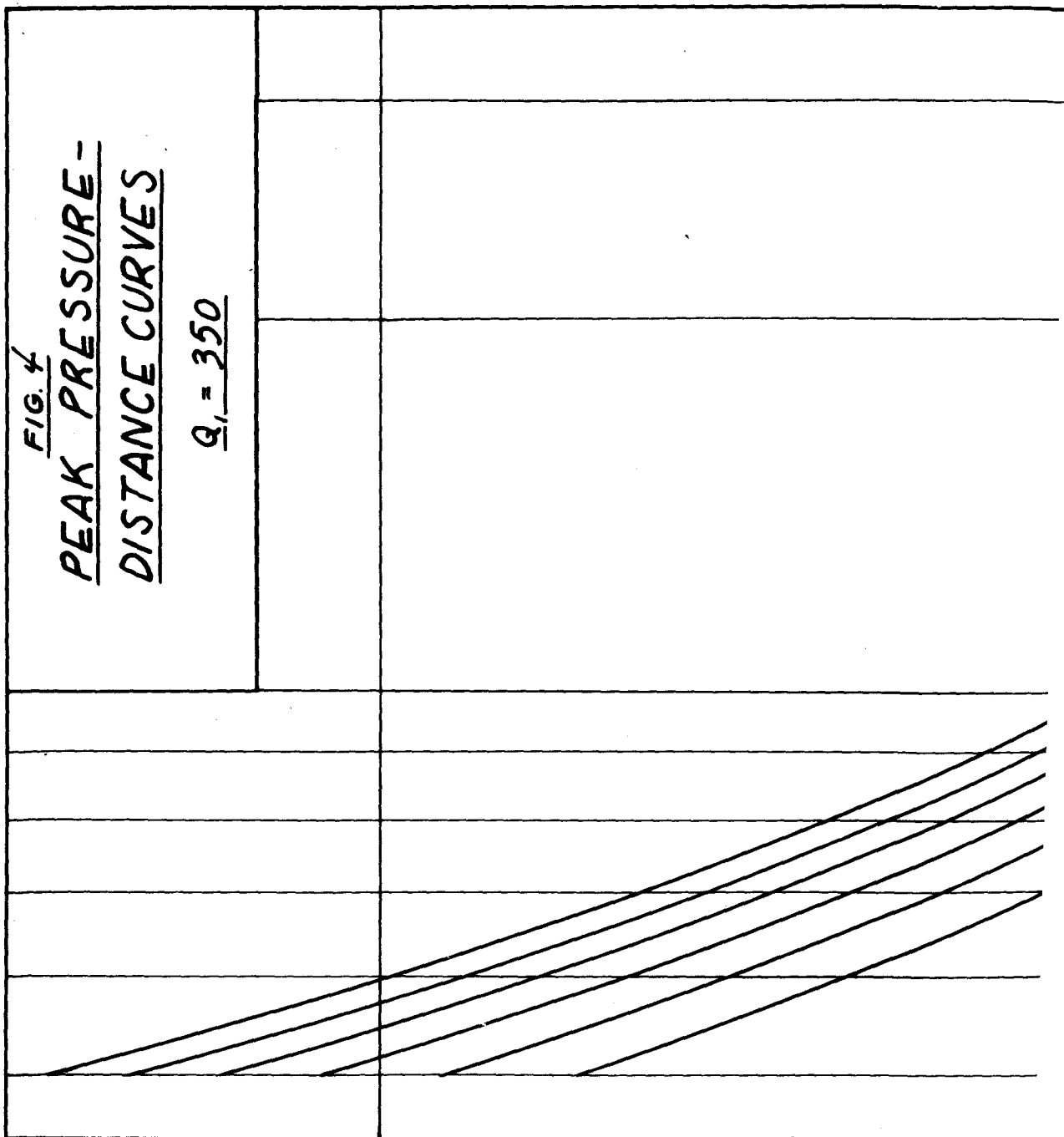


$PR(p_0/W)$

2/2

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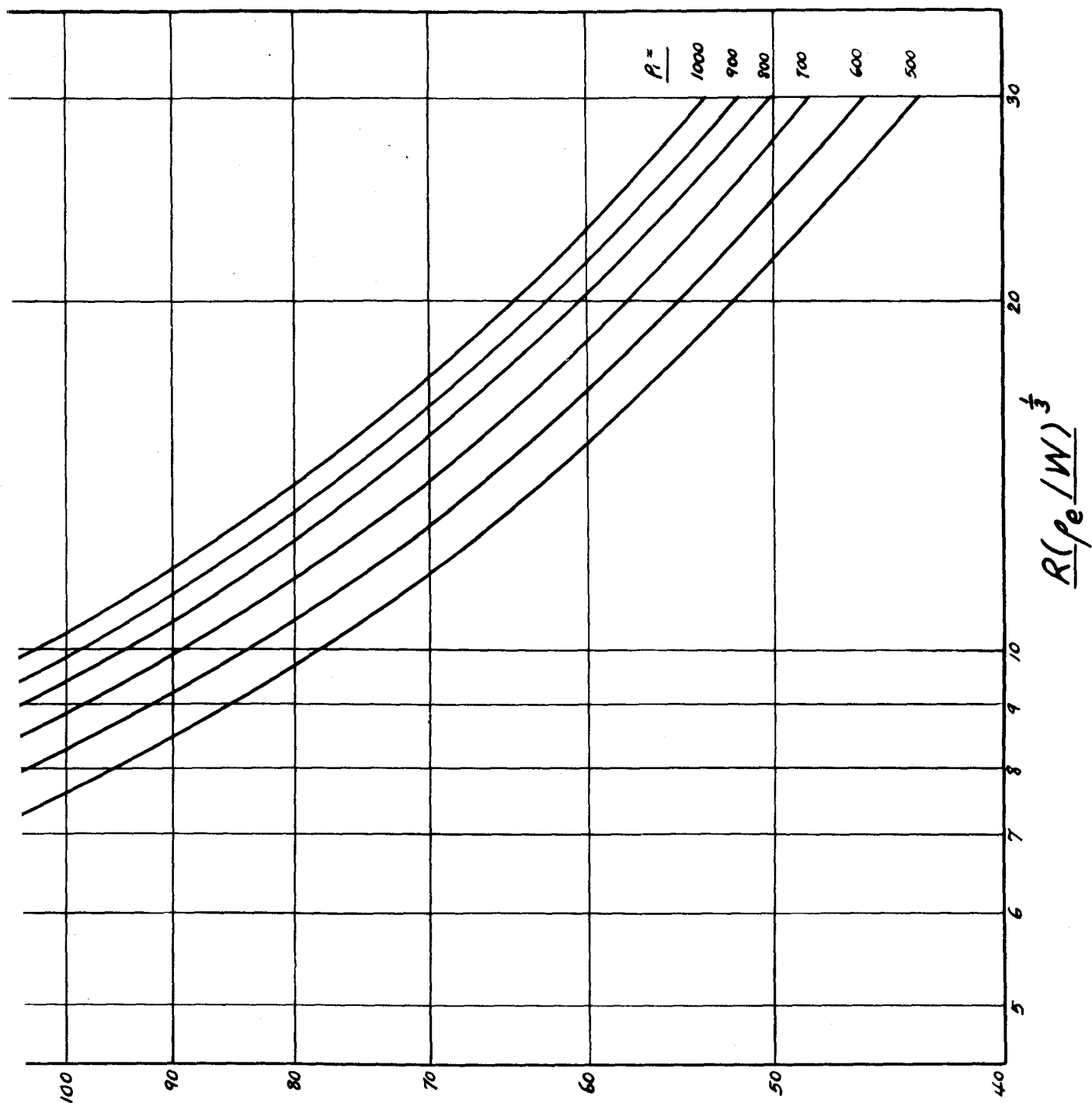
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200

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$R(p/W)^{1/3}$



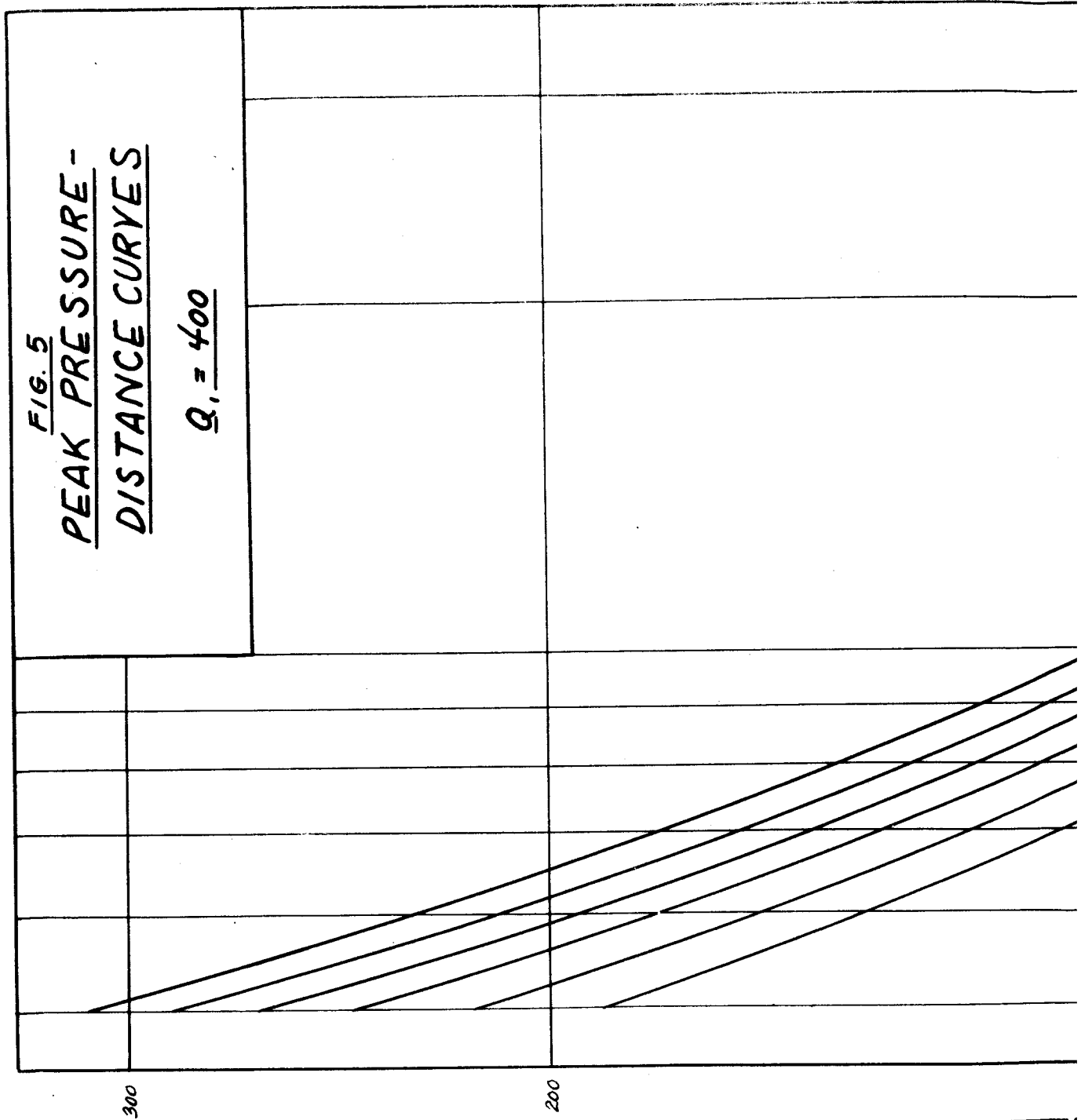
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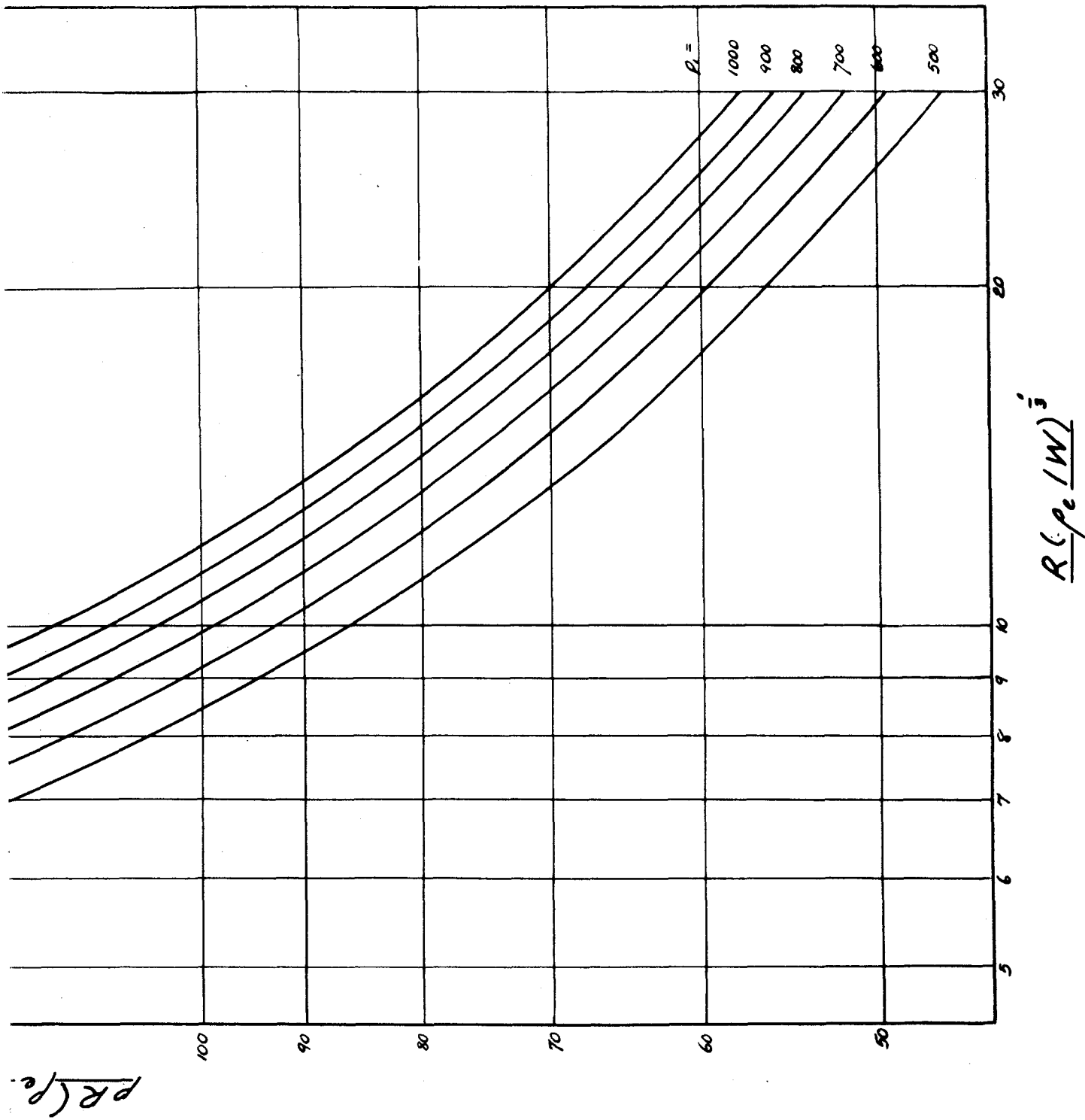
FIG. 5
PEAK PRESSURE -
DISTANCE CURVES

$Q_1 = 400$



10/2

10/2 (M)



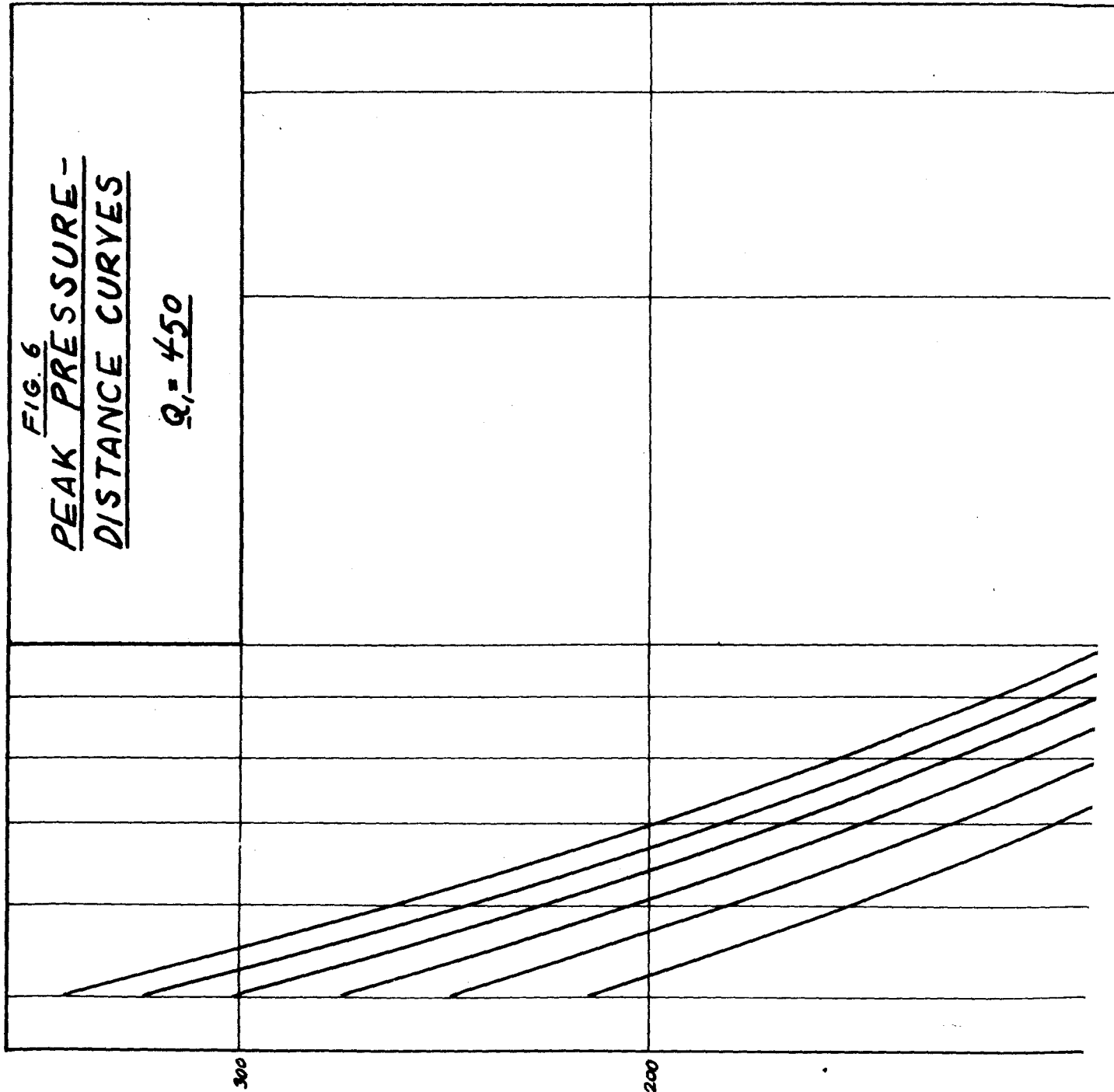
262

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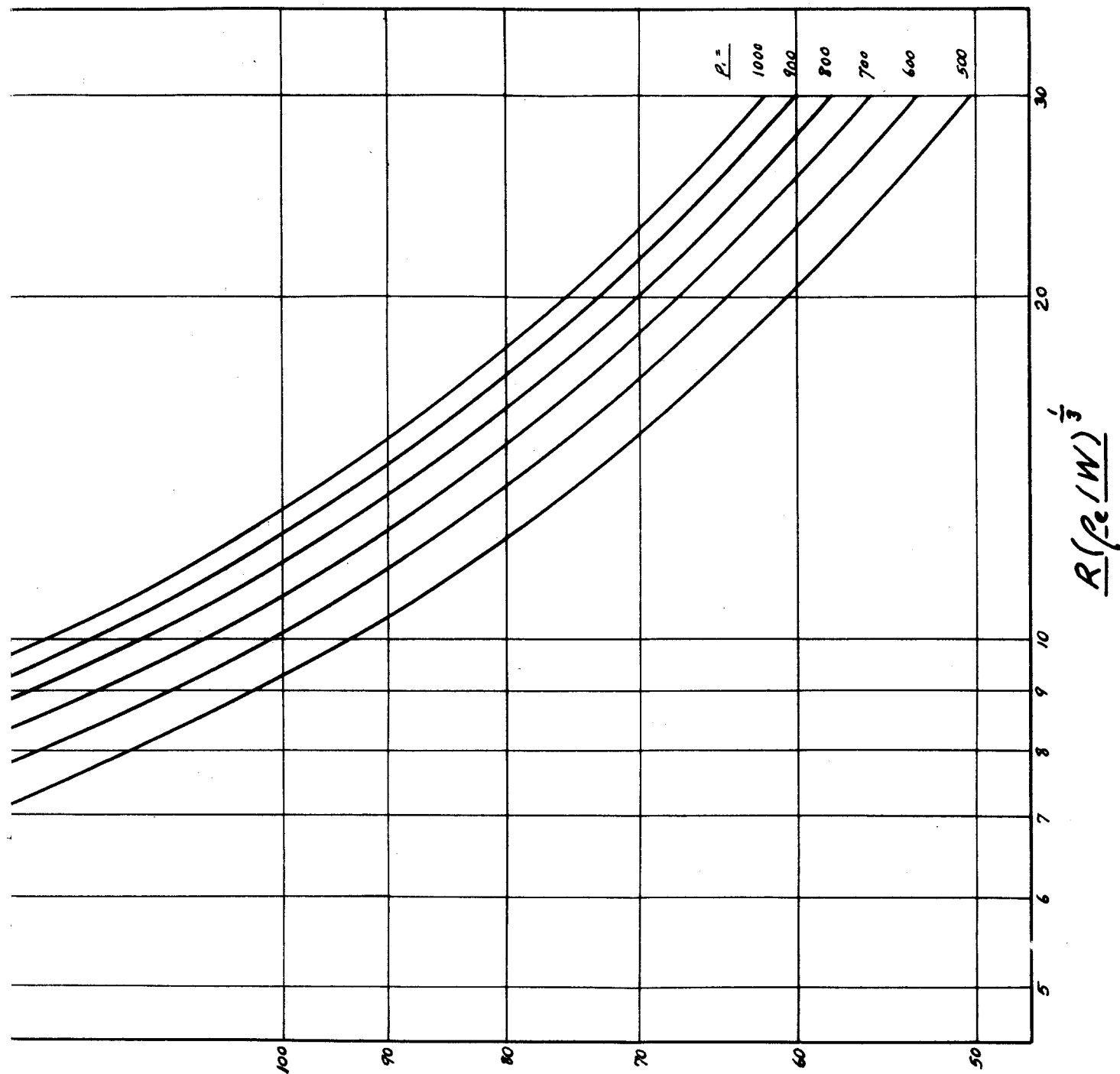
FIG. 6
PEAK PRESSURE-
DISTANCE CURVES

$Q_1 = 450$



182

100 (M)

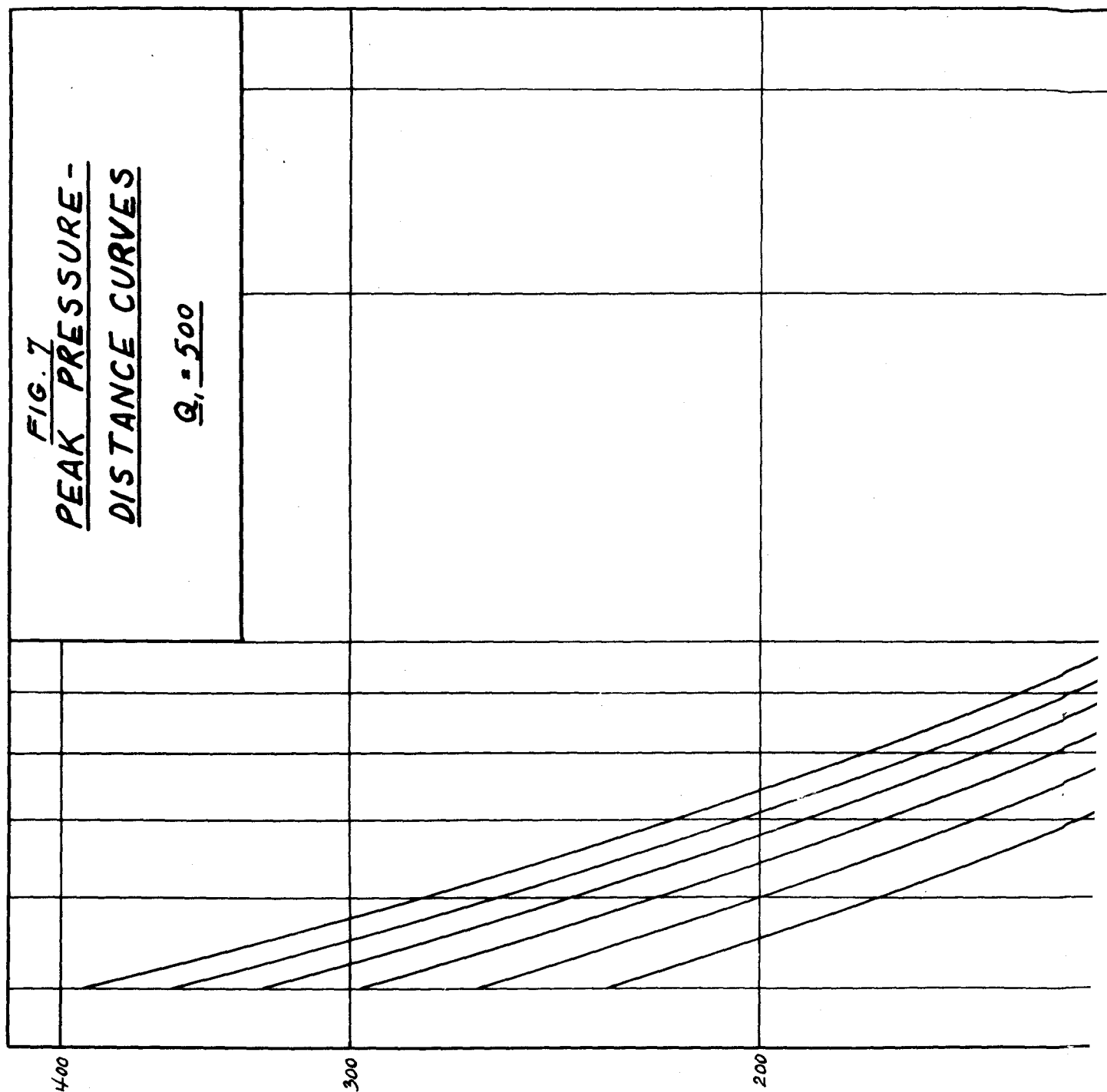


p_e

282

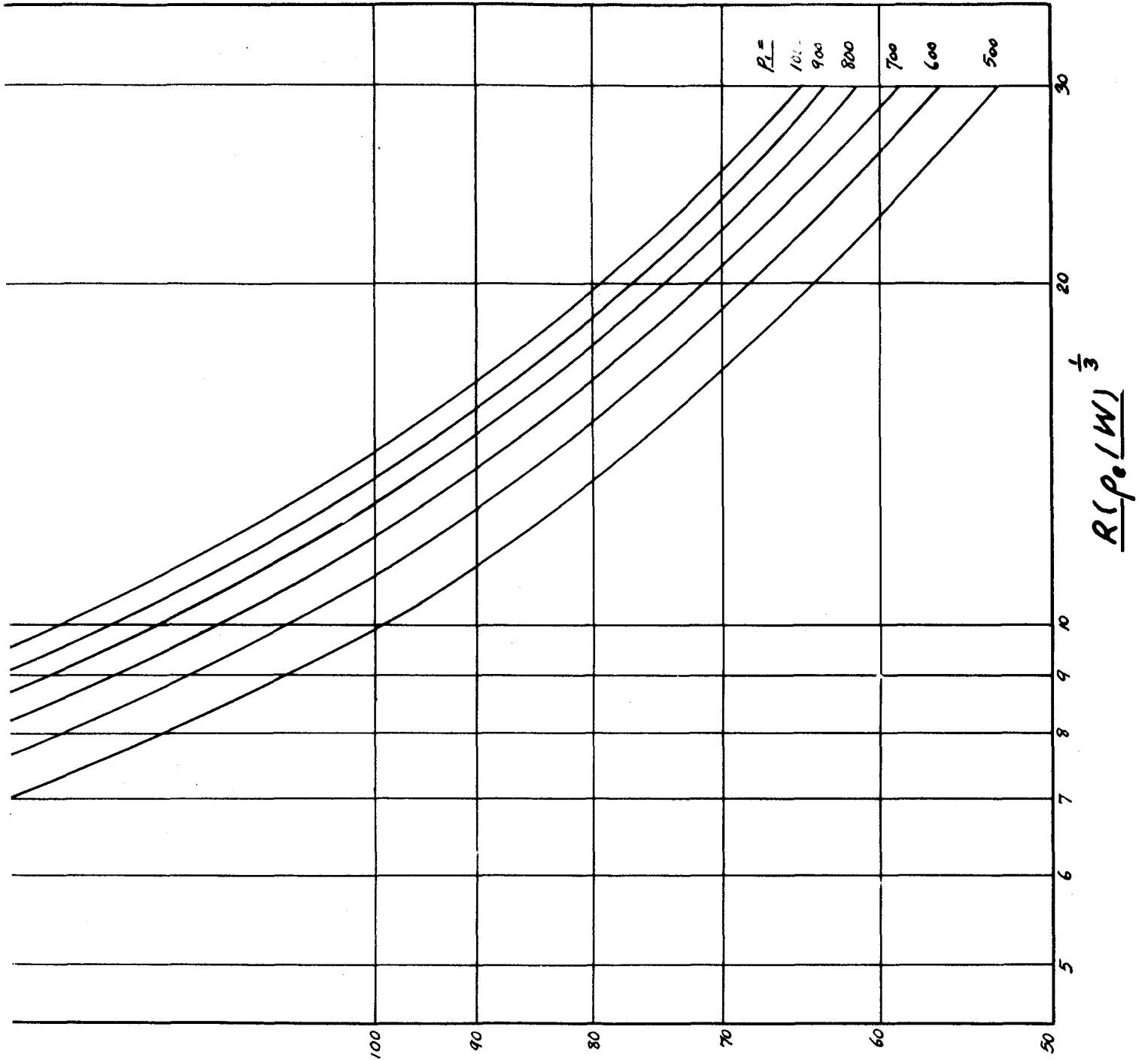
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1 (M) 3



pR/p_o

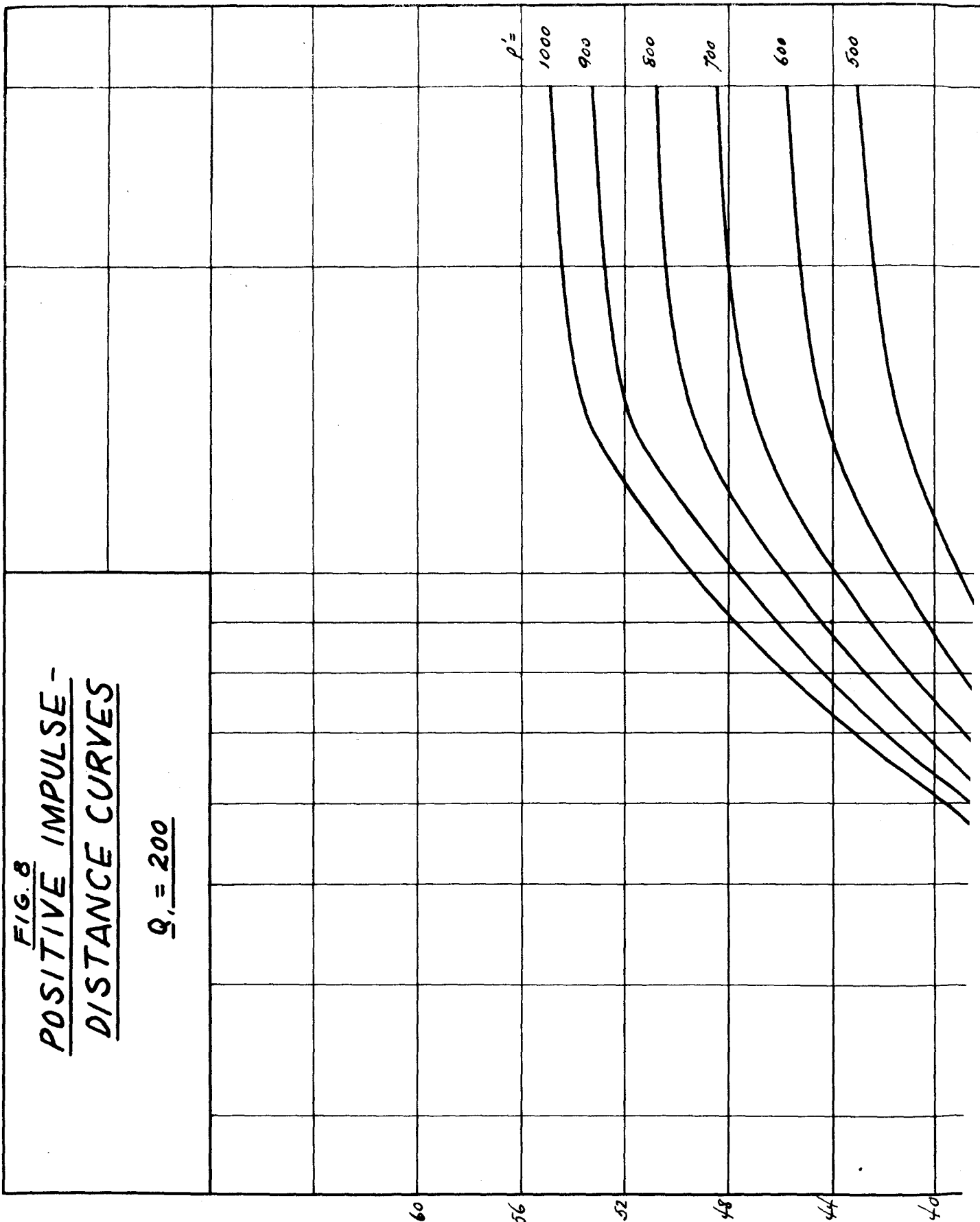
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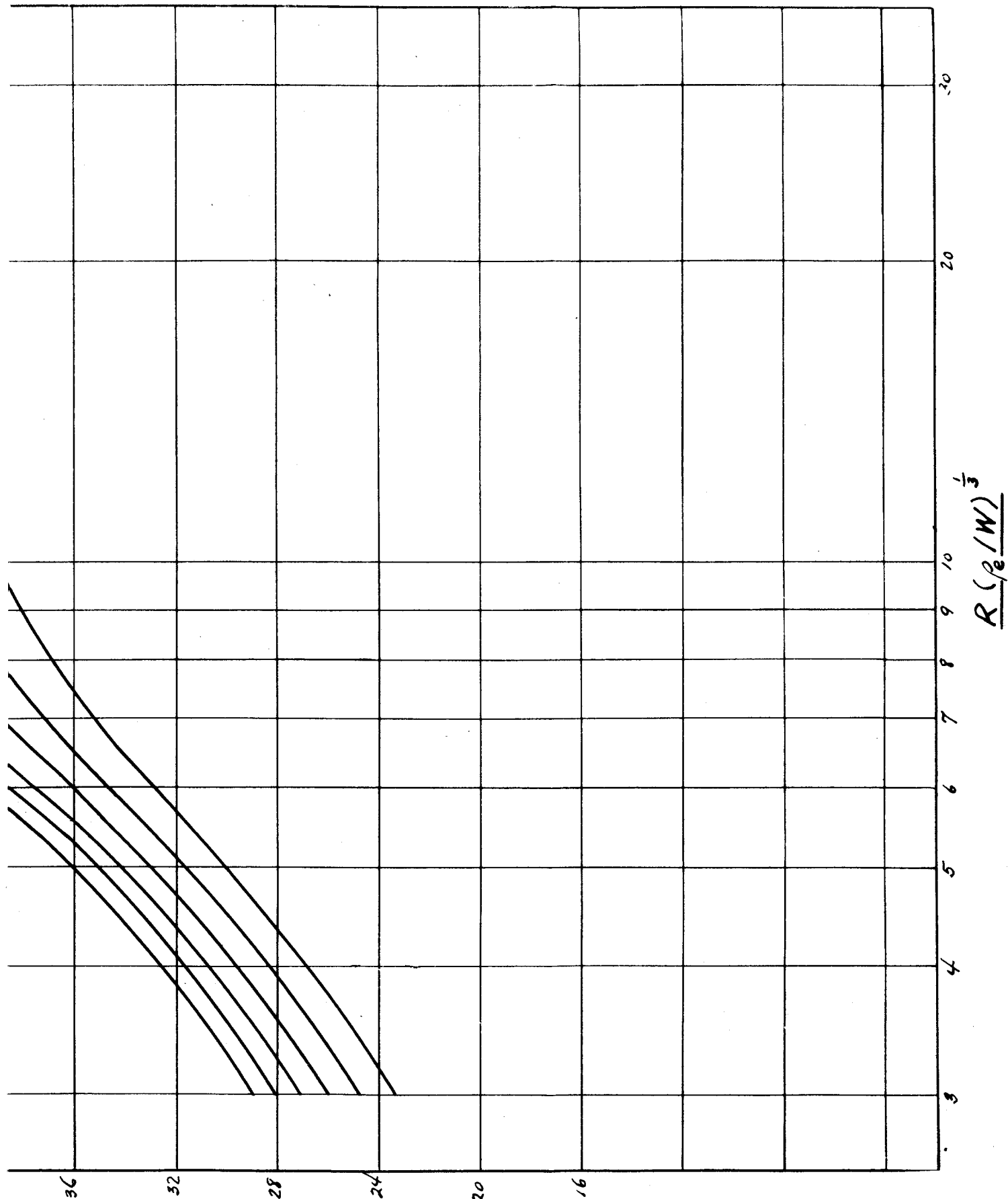
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FIG. 8
POSITIVE IMPULSE-
DISTANCE CURVES

$Q_1 = 200$

1 of 2
 $\rho_e (M)^{20}$

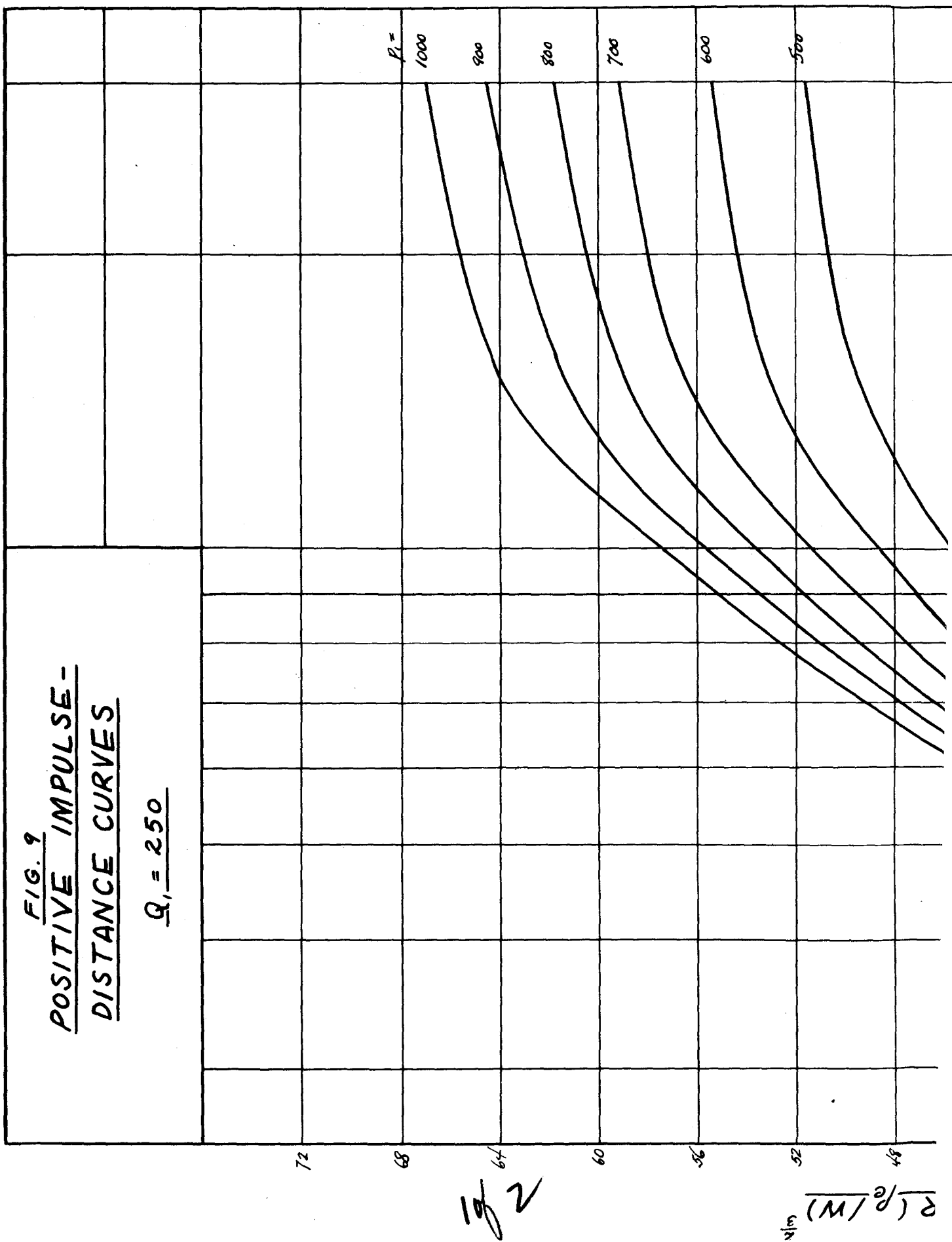




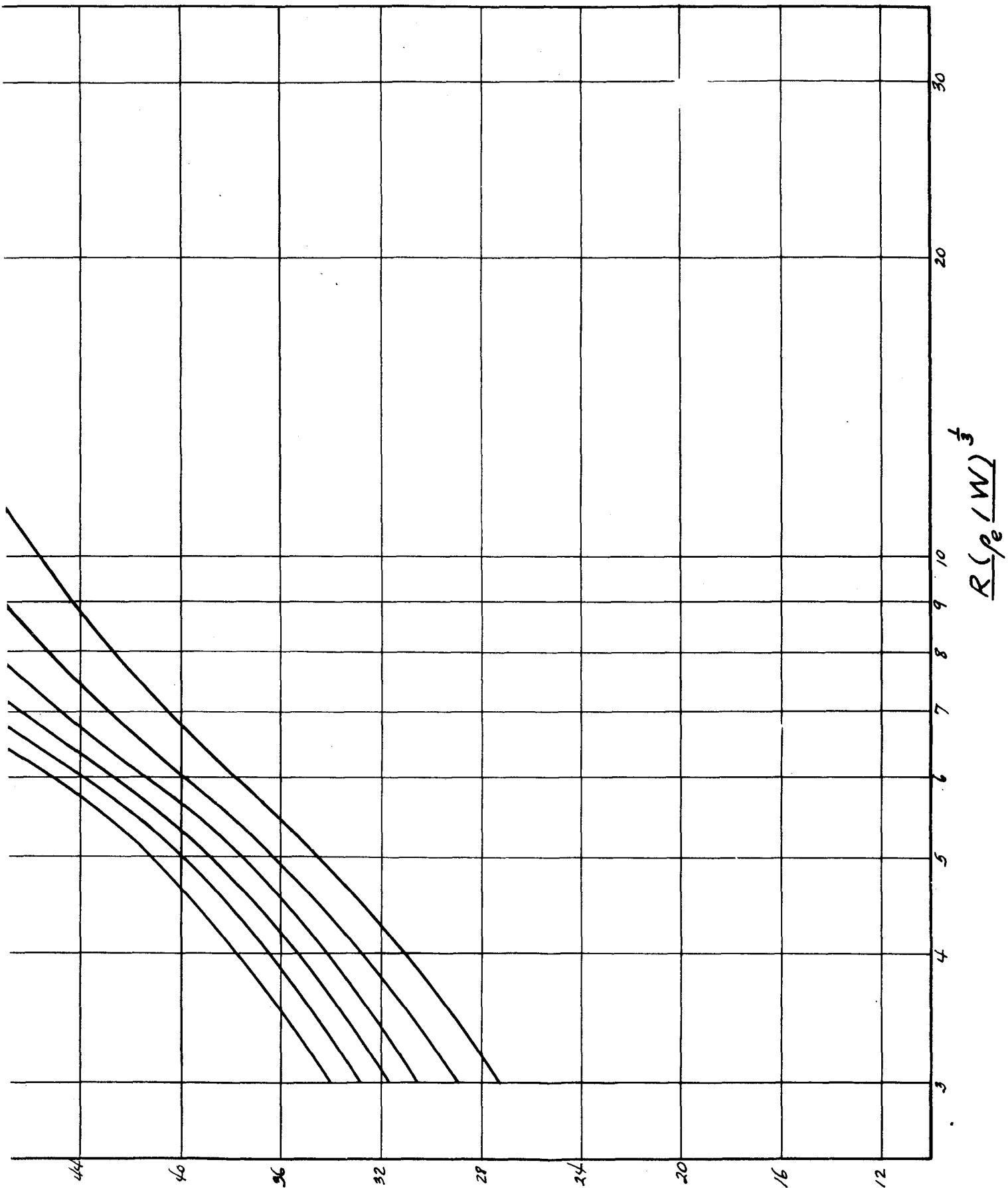
$10^3 RI$

202

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182

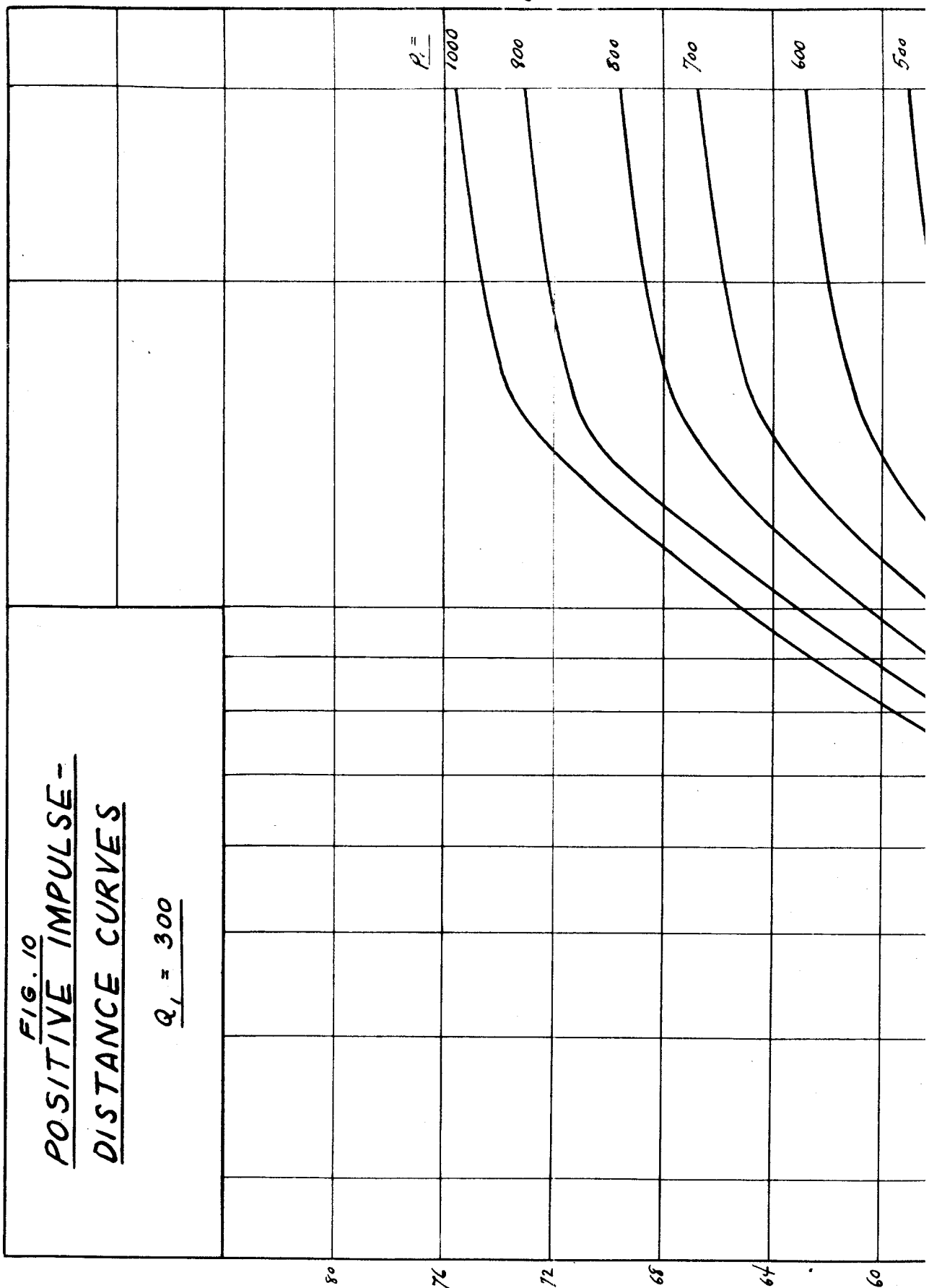


20/2

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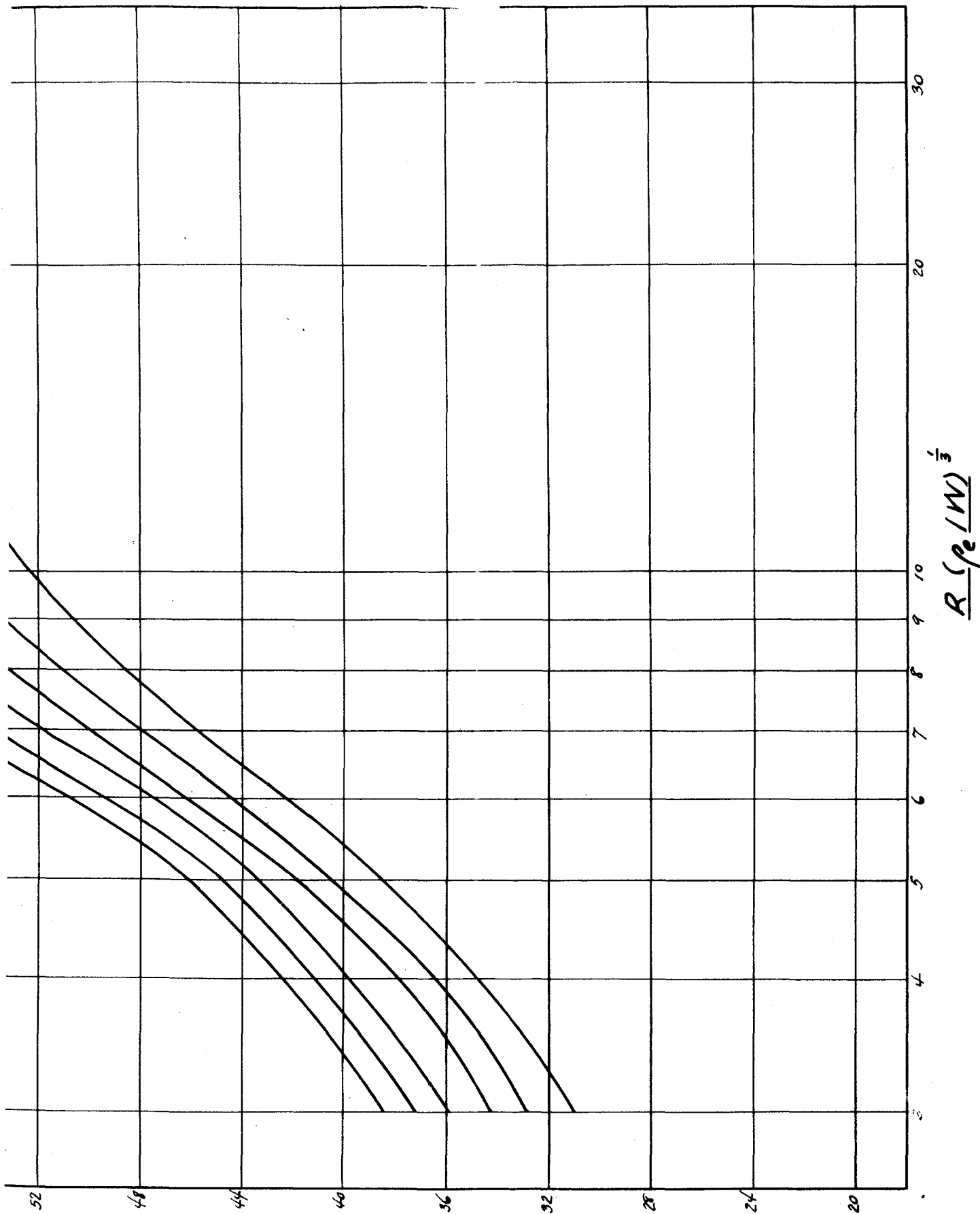
FIG. 10
POSITIVE IMPULSE-
DISTANCE CURVES

$Q_1 = 300$



M

2002



101

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FIG. 11
POSITIVE IMPULSE -
DISTANCE CURVES

$Q_i = 350$

88

84

80

76

72

68

$P_i =$
1000

900

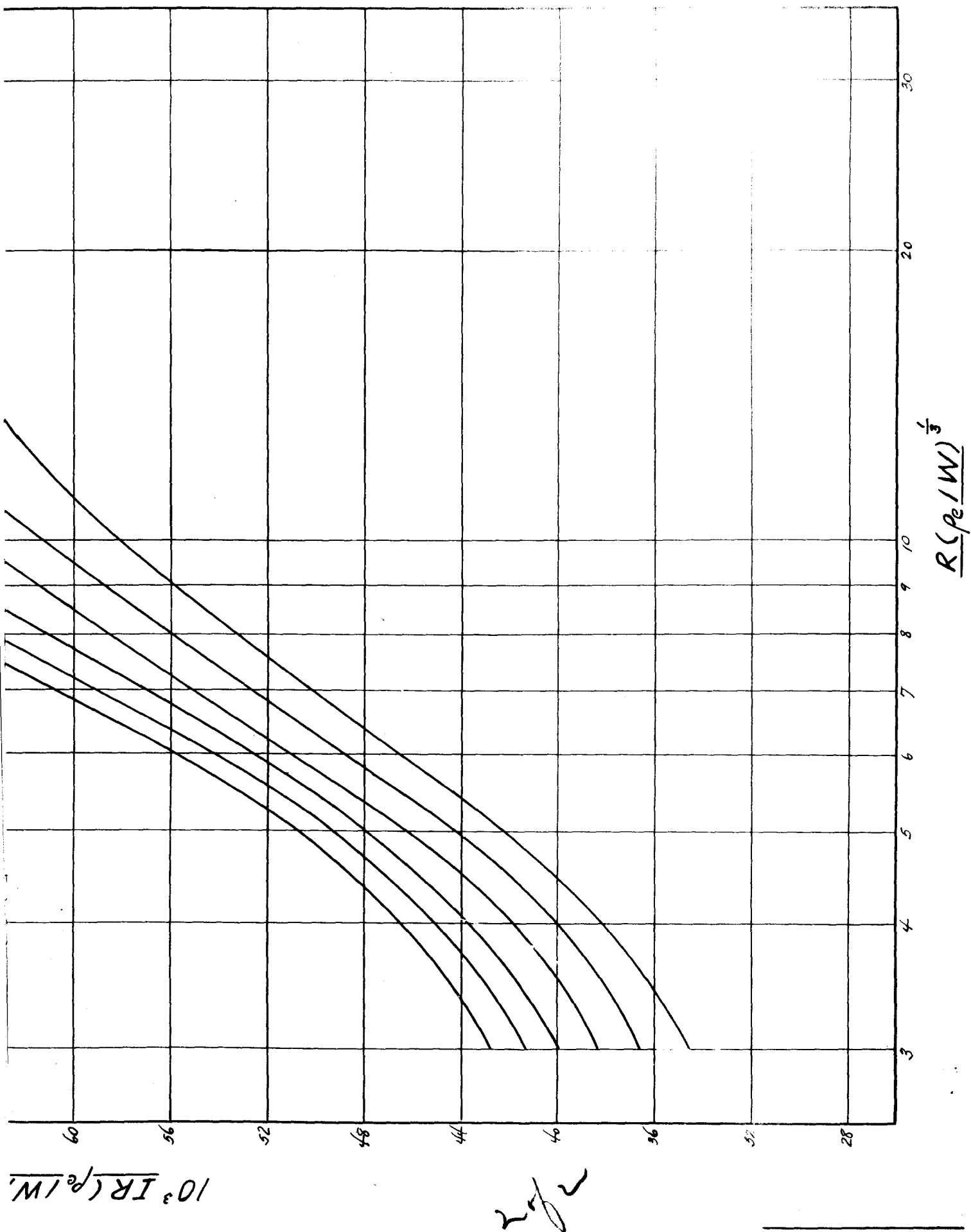
800

700

600

500

152



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FIG. 12
POSITIVE IMPULSE-
DISTANCE CURVES

$Q_1 = 400$

$P_1 =$

1000

900

800

700

600

500

96

92

88

84

80

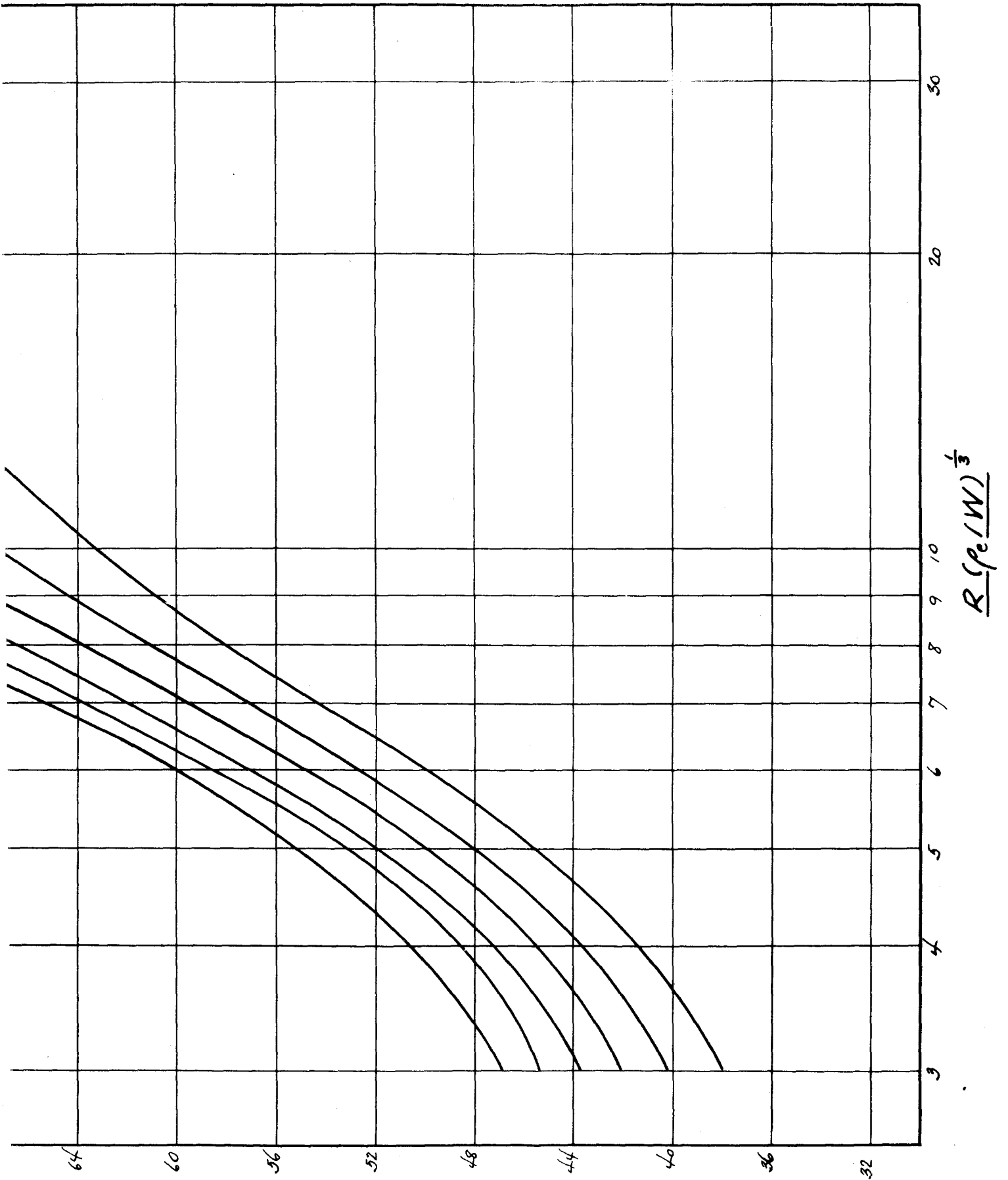
76

72

68

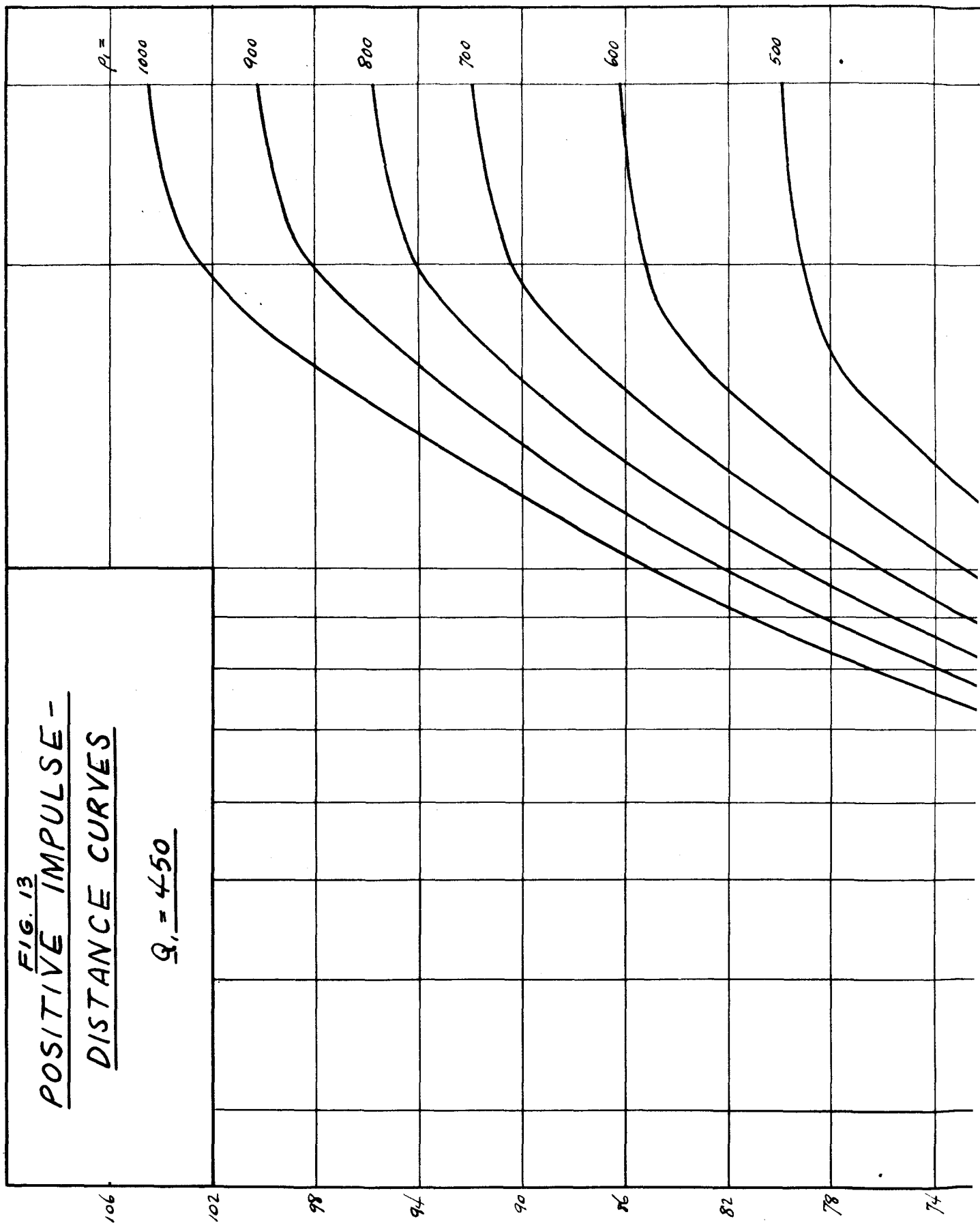
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1/2



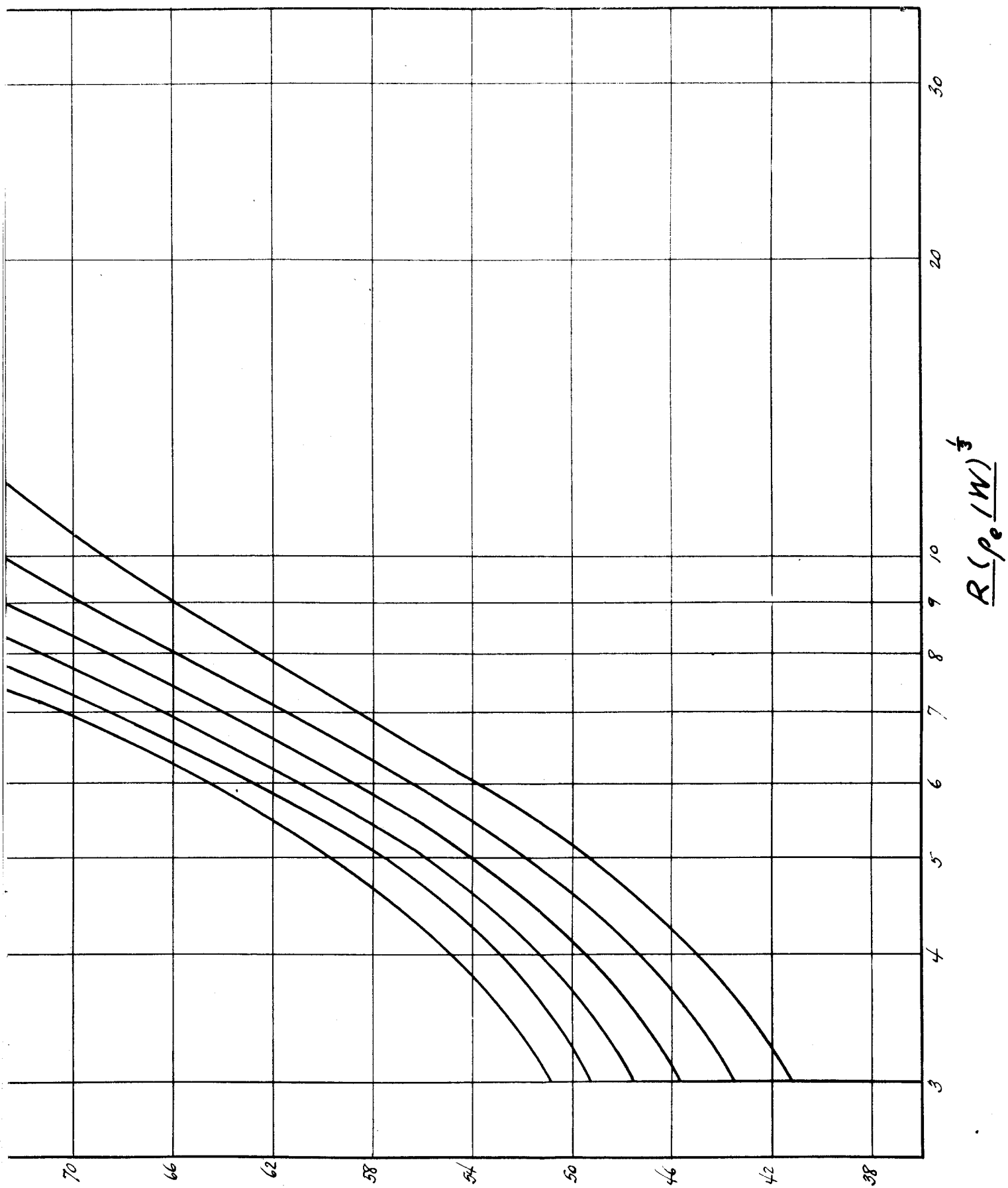
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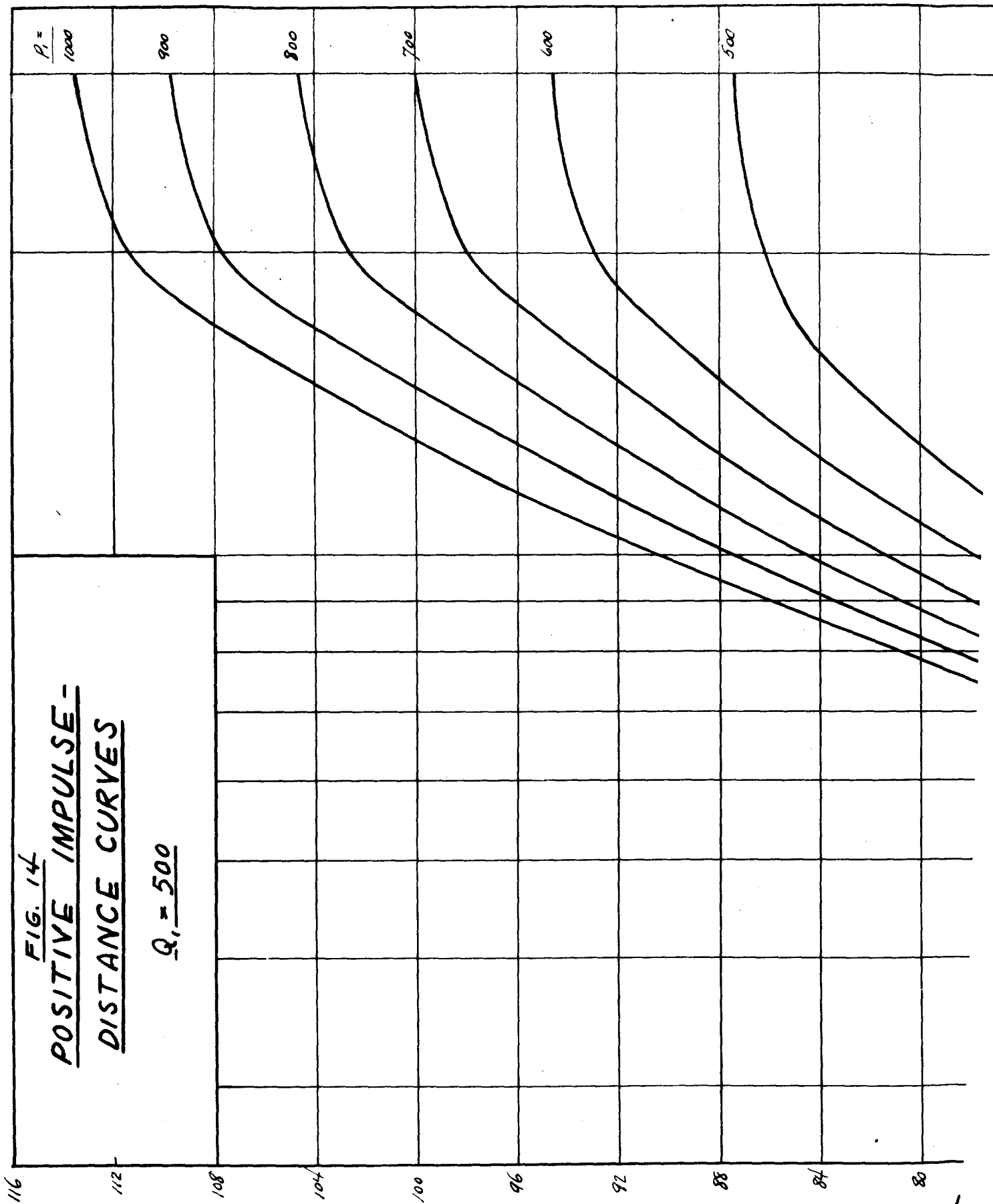
10/2

$\frac{1}{2} \log (M^2 d)$



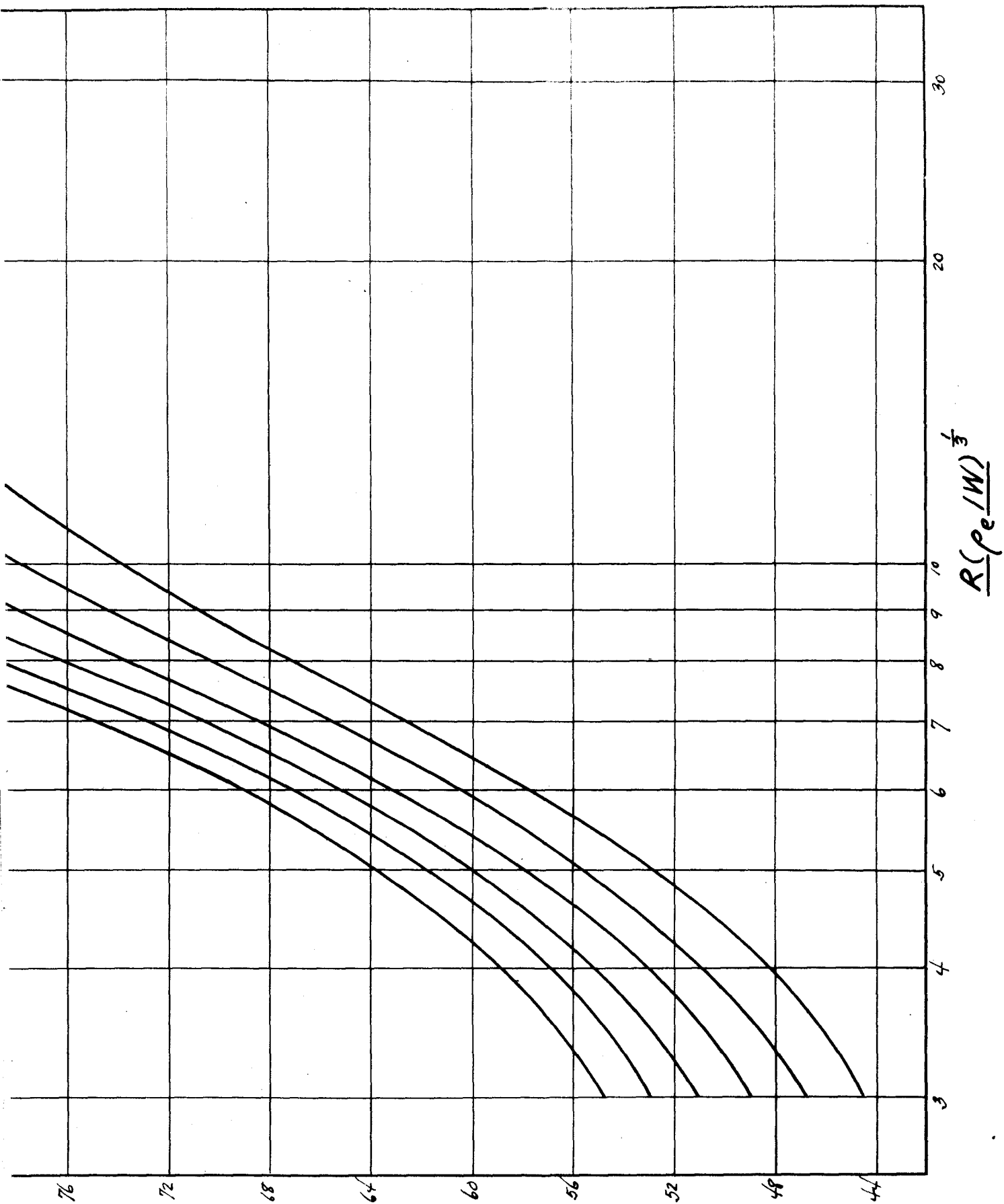
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2001

$P_1(M)$



10³IR

2062

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III. BLAST-WAVE CURVES FOR CAST TNT

The peak pressure, shock-wave energy, and positive impulse of the blast wave produced by cast TNT have been estimated, employing the procedure described in Part I for the determination of the initial parameters from experimental peak pressures measured at large distances from the charge. We have chosen peak pressures recently determined by the shock-velocity method^{4/} in preference to those determined by piezoelectric-gauge measurements because of present gauge-calibration difficulties which may necessitate revision of the results obtained by the latter method.^{5/} The shock-velocity method does not lead simultaneously to measurements of the positive impulse, and therefore the initial parameters were determined from peak pressures alone. The experimental measurements were made at the Underwater Explosives Research Laboratory.^{6/}

The experimental values of the peak pressure are listed in Table IV. As a result of the visual curve-fitting, the three pairs of initial parameters listed in Table V were selected. Since standard deviations for the experimental points were not determined, each deviation of experimental peak pressure from the corresponding theoretical value was given unit weight in computing the mean-square deviation of the experimental values from the theoretical values. From a consideration of these mean-square deviations, listed in Table V, the parameter set $p_1 = 550$, $Q_1 = 450$

Table IV. Experimental peak pressures for TNT.

$R/W^{1/3}$	P (lb/in ²)
6.56	17.5
7.90	11.6
15.0	3.65

Table V. Mean-square deviations of experimental peak pressures from selected members of the family of theoretical peak-pressure curves.

Q_1	p_1	Δp^2
350	800	0.224
400	650	.208
450	550	.114

^{4/} T. D. Carr, M. Schwarzschild, and P. Weiss, An improved method for the measurement of blast from bombs, Aberdeen Proving Ground Ballistics Research Laboratory Report No. 336.

^{5/} A. B. Arons, C. W. Tait, G. K. Frankel, and K. M. Deane, "Characteristics of air-blast gauges: Response as a function of pressure level," Monthly Report AES-8a (OSRD-4875a).

^{6/} W. D. Kennedy (UERL), Private communication, April 1945.

was chosen as affording the best representation of the experimental points. The individual deviations of the selected theoretical points from the corresponding experimental points is shown in Table VI.

Table VI. Comparison of experimental peak pressures for TNT with the theoretical peak pressure-distance curve for which $Q_1 = 450$, $p_1 = 550$.

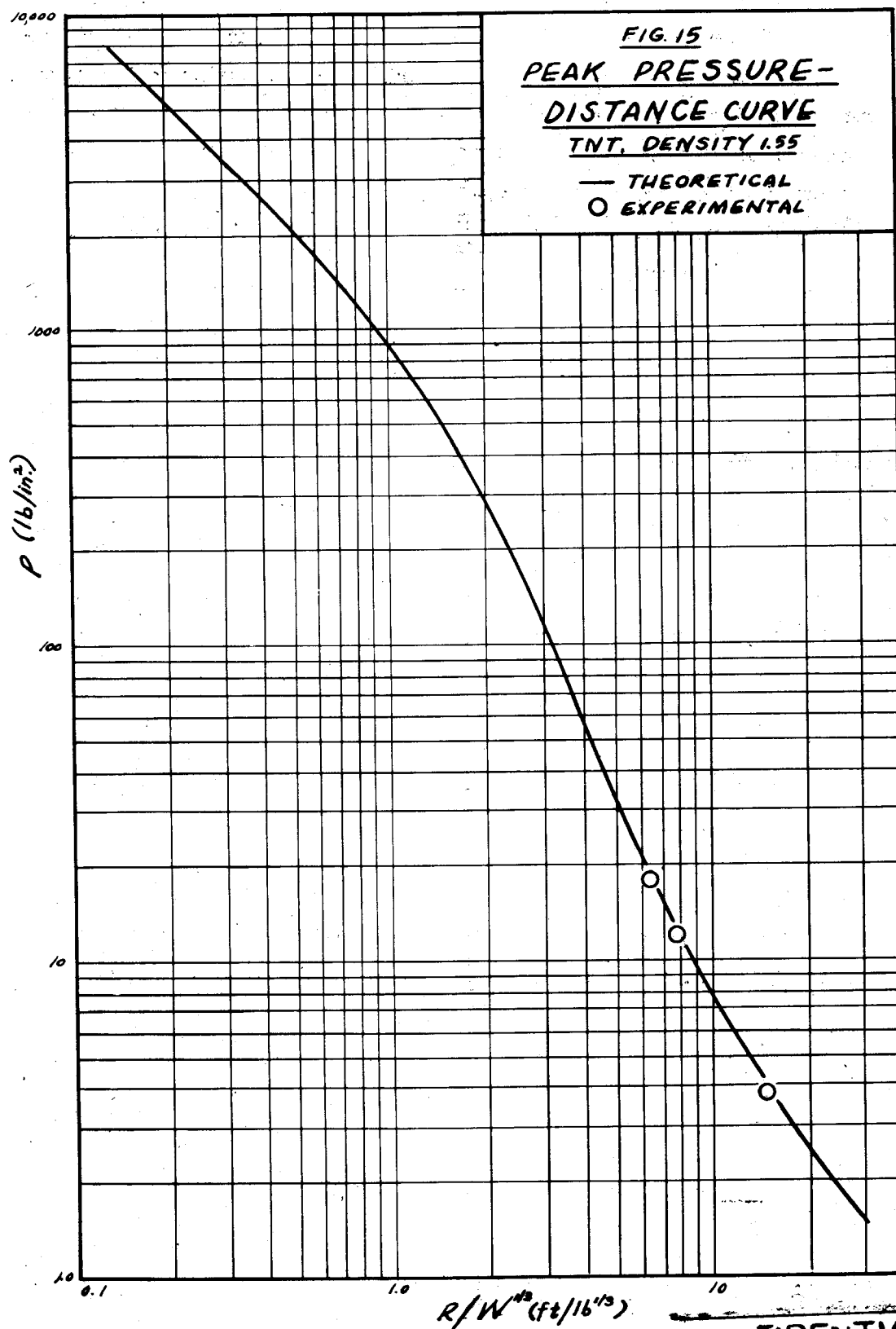
$R/W^{1/3}$ (ft/lb ^{1/3})	p (lb/in ²)		Deviation (percent)
	Experimental	($Q_1 = 450$, $p_1 = 550$)	
6.56	17.5	17.0	2.9
7.90	11.6	11.6	0.0
15.0	3.65	3.83	4.7
Average 2.5			

The complete peak pressure-distance, energy-distance, and positive impulse-distance curves for cast TNT were constructed from Tables I to III, employing the initial parameters as determined above. These results are listed in Table VII, and the peak pressure-distance curve is shown in Fig. 15. Interpolation of the tabulated quantities to rounded values of $R/W^{1/3}$ was performed graphically.

Table VII. Properties of the blast wave produced by TNT, density 1.55.

		Symbol	Unit			Symbol	Unit
		R	ft			I	lb-sec/in ²
		W	lb			ϵ	kcal/gm
		p	lb/in ²				
$R/W^{1/3}$	p	ϵ	$10^3 I/W^{1/3}$	$R/W^{1/3}$	p	ϵ	$10^3 I/W^{1/3}$
0.135	7960	1.17	7.48	3.0	119	0.600	11.1
.2	5330	1.16	9.74	5.0	32.2	.363	8.18
.3	3540	1.16	12.5	7.0	15.1	.265	6.90
.5	2080	1.14	16.6	10	7.55	.201	5.56
.7	1420	1.11	18.3	15	3.85	.157	4.04
1.0	912	1.05	19.1	20	2.51	.135	3.13
1.5	490	0.932	16.9	30	1.43	.101	2.04
2.0	292	0.830	14.5				

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The initial pressure for TNT of 7960 lb/in² is lower than the values previously estimated^{1/} of 10400 lb/in² for Pentolite and 8076 lb/in² for Torpex 2. The initial shock-wave energy of 1.17 kcal/gm for TNT is to be compared with the values 1.45 kcal/gm for Pentolite and 1.26 kcal/gm for Torpex 2. The heat of explosion of TNT has been estimated to be 1.06 kcal/gm. The higher value of the initial shock-wave energy is evidence for afterburning of the products of explosion with atmospheric oxygen, although the amount of energy contributed by such afterburning is difficult to estimate since a part of the energy of the explosion products will contribute to secondary shocks. As shown in the earlier report,^{1/} the tabulated values of the properties of the blast wave represent lower limits to the actual values during such time as afterburning is effective.

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TITLE: Tables and Graphs of the Theoretical Peak Pressures, Energies, and Positive Impulses of Blast Waves in Air AUTHOR(S): Brinkley, S. R.; Kirkwood, John G. ORIGINATING AGENCY: Office of Scientific Research and Development, NDRC, Washington, (D.C.) PUBLISHED BY: (Same)						
DATE May '45	DOC. CLASS. Conf'd	COUNTRY U.S.	LANGUAGE Eng.	PAGES 37	ILLUSTRATIONS tables, graphs	
ABSTRACT: Two-parameter families of curves for blast waves from explosive sources in air are presented. Determination of parallels is made from experimental values of peak pressure and positive impulse over limited range of distance. Peak pressure, shock wave energy, and positive impulse of blast wave produced by cast TNT are given. High value of shock wave energy is evident for afterburning of product of explosion with atmospheric oxygen.						
DISTRIBUTION: Copies of this report obtainable from Air Documents Division; Attn: MCIDXD DIVISION: Ordnance and Armament (22) SECTION: Explosives (6)						
ATI SHEET NO.: C-22-6-23 Air Documents Division, Intelligence Department Air Materiel Command			SUBJECT HEADINGS: Explosives - Blast waves - Calculation (34440); Shock waves (88300); Blast effects (18210) AIR TECHNICAL INDEX CONFIDENTIAL			
Wright-Patterson Air Force Base Dayton, Ohio						

265650

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 15 Feb - 2 August 46

* Blast Waves
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